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STUDY OF SUSPENDED SEDIMENT TRANSPORT IN THE DOKRIANI GLACIER MELT STREAM

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CONTENTS

Preface

Most of the studies in our country are carried out for the plain rivers or for some rivers in the lower part of the Himalayas. Sedimentation study for high altitude glacierized basins in the Himalayas are very limited. The same is true for the Himalayan glaciers where systematic studies are lacking. Only few studies based on the limited time period are available for few specific glaciers. These studies can not be generalized even for the near by glacier because of changes in geology and topography. Estimation of sediment load from the high altitude region, where glaciers exist, is very important for planning, designing, installation and operation of hydro-power projects including management of reservoirs.

In the present study, assessment of suspended sediment concentration, load, yield and erosion rate has been made for a highly glacierized Dokriani Glacier basin located in the Garhwal Himalayas. This report also presents the status of the sediment studies carried out in the Himalayan region including the both lower altitude region and high altitude region. Processes associated with sediment production in the mountainous region have also been described with an emphasis on the glacierized region. Suspended sediment concentration and load observed in the Dokriani Glacier melt stream near the snout of the glacier has been computed. Sediment yield from this glacier is found to be very high as compared with other Himalayan basins. Attempts have been made to correlate sediment concentration and load with glacier melt runoff

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Abstract

Estimation of sediment load from the glacierized basins is very important for planning, designing, installation and operation of hydro-power projects including management of reservoirs. In the present study, assessment of suspended sediment concentration, load, yield and erosion rate has been made for a highly glacierized Dokriani Glacier basin located in the Garhwal Himalayas. Mean monthly concentration in the month of June, July, August and September were observed to be 452, 933, 965 and 275 ppm, respectively. Mean monthly sediment concentration in the months of July and August was found about two times that of June and about three times that of September. A very high quantity of sediment load has been observed from the study basin. Seasonal distribution of sediment load shows that on average 3607, 18733, 20951 and 1794 tonnes is transported in June, July, August, and September, resulting in 45085 tonnes during ablation period. Both sediment concentration and load were found maximum in the month of August followed by July. About 88% of the total sediment load is transported in the months of July and August. Poor relationship is found between suspended sediment concentration and load with discharge.

Sediment yield for the melt period is computed to be about 2800 t km^{-2}yr^{-1}, which is comparable with glacierized basins in the Pamir region. The erosion for Dokriani glacier basin is estimated to be about 2.0 mm for the ablation period, which is higher than the erosion rate reported by other investigators for the glacierized basins in Europe. Average percentage of clay, silt and sand was found to be 1.4, 67.3 and 31.3%, indicating maximum content of silt followed by sand. There was no very significant variation in the content of clay, silt and sand in the suspended sediment during the ablation period.

This report presents the status of the sediment studies carried out in the Himalayan region including the both lower altitude region and high altitude region. Processes associated with sediment production in the mountainous region have also been described with an emphasis on the glacierized region. Suspended sediment concentration and load observed in the Dokriani Glacier melt stream near the snout of the glacier has been computed. Sediment yield from this glacier is found to be very high as compared with other Himalayan basins. Attempts have been made to correlate sediment concentration and load with glacier melt runoff. Poor relationship is found between these variables. Analysis of suspended sediment particle size has indicated that average percentage of clay, silt and sand was found 1.4, 67.3 and 31.3%, indicating maximum content of silt followed by sand. There was no significant variation in the content of clay, silt and sand was found during the ablation period. Both sediment concentration and load were poorly correlated with discharge. However, relationship between discharge and sediment load was improved when monthly data were used.

1.0 INTRODUCTION

In India an area of about 1,750, 000 km^2 out of the total land area of 3,280,000 km^2, i.e., 53% of total land area is prone to soil erosion (Narayana and Ram Babu, 1983). The accelerated soil erosion has irreversibly converted vast tracts of land into infertile surfaces over the country. These degraded land surfaces have also become a source of pollution of the natural water. Deposition of soil eroded from upland areas in the downstream reaches of rivers has caused aggradation. This has resulted in an increase in the flood plain area of the rivers, reduction of the clearance below bridges and culverts and sedimentation of the reservoirs.

The rivers emerging out from the Himalayan region transport the sediment at a very high rate. The other regions of India with most spectacular erosion is the severely eroded gullied lands along the banks of Yamuna, Chambal, Mahi and other west flowing rivers in Gujarat and the southern rivers, namely, the Cauvery and the Godavari river systems. As a result, agricultural production is greatly affected on the red soils which cover an area of 720000 km^2 in the basins of the Chambal and Godavari (Verma et al., 1968). The depth of these soils is limited to 200 mm, in most of these areas. The lateritic soils which are associated with rolling and undulating topography have been found to lose about 4000 t km^{-2} of valuable top soil annually due to erosion in Peninsular India (Babu, R. et al., 1978). The black soils, occupying nearly 640,000 km^2, are usually utilized for crop production under rainfed conditions. Surprisingly, these lands are normally cultivated and kept fallow during the intense rainy season, making them susceptible to serious erosion.

Sandy and eroded drainage basins situated in regions characterized by occasional and sporadic torrential rainfall generate high sediment yields. Coarse to medium grained, loose and less compact formations generate more sediment with increasing rainfall and drainage basin slope than the fine grained, hard and compact formations (Sharma, 1996). In recent years, it has been confirmed that high sediment yields are associated with arid/semiarid, seasonal mediterrranean, and tropical conditions (Walling and Webb, 1983). A compilation of sediment yields for meso-scale drainage basins suggests that arid basins export 36 times more material than humid temperate and 21 times more than humid tropical equivalents (Reid and Frostick, 1987). Bare soil is highly susceptible to rain splash and wash erosion, and arid zones produce record suspended sediment concentrations (Jones, 1981). The sediment not only causes water quality to deteriorate but also affects physical and biological conditions in the receiving systems. In the Indian arid zone, the storage capacity of small reservoirs (400 to 700000m^3) is reduced by 1.9 to 7.8% annually due to sediment deposition (Sharma and Joshi, 1982). Soil and water conservation for watersheds is currently receiving high priority in India because of its impact on both the protection of the badly eroded land and its various resources, and on improvement of production of such lands. Since 1951, soil conservation measures were adopted on only 250,000

km^2 of area (Deptt. of Agriculture and Co-operation, Government of India, 1982).

The entire Himalayan region is afflicted with a serious problem of soil erosion and rivers flowing through Himalayan region transport a heavy load of sediment. Himalayan and Tibetan region cover only about 5 percent of the Earth's land surface, but supply about 25 percent of the dissolved load to the world oceans (Raymo and Ruddiman, 1992). A total of 1.8×10^9 tonne yr^{-1} of suspended sediment (about 9% of the total annual load carried from the continents to the oceans worldwide) is transported in three major river systems; the Brahamaputra, Ganga and Indus; in a combined runoff of 1.19×10^3 km^3 (Meybeck, 1976). About 75% of the runoff in these three major rivers occur between June and September, in response to the monsoonal precipitation, snow and glacier melt (Collins and Hasnain, 1995). Current estimates of sediment yield of the Ganga and the Brahmaputra rivers together is about 1.0×10^9 tonnes $year^{-1}$ (Subramanian, 1993), compared with the global annual sediment flux of about 15×10^9 tonnes $year^{-1}$ (Milliman and Meade, 1983). Contemporary rates of denudation in the Himalayas are undoubtedly high in comparison with continental averages, as might be expected in an area of recent and continuing tectonic activity. The Himalayan rivers draining the tectonically active belts, show a very high sediment yield. The ongoing interaction of Indian and Eurasian plates maintain uplift, and high elevations ensure large glaciers and steep unstable slopes which maintain sediment supply to the rivers of the subcontinent (Collins and Hasnain, 1994).

The natural factors that lead to high levels of sediment transport from the region are the steepness of the terrain, the tectonic instability of the area, the relatively young age of the mountains, the large and active glaciers, the high intensity monsoonal rainfall and natural weathering processes. In the high mountain regions, glaciers scour the mountain slopes and transport rock and boulders to the lower valleys. Steep topographic gradient and poor structural characteristics of soils available on these slopes and in the valleys become an important factor for high rate of sediment erosion. Anthropogenic intervention, which includes mainly deforestation, road construction, mining, unscientific farming, overgrazing on the slopes and other developmental projects, has also accentuated the processes of soil erosion. The anthropogenic intervension has disturbed ecosystems in the past due to over exploitation in many parts of the world, including some parts of India. The resulting imbalance in the ecosystem has caused various undesirable effects, such as degradation of soil surfaces, frequent occurrence of intense floods etc.

In the Himalayan mountains, as a consequence of loss of forest cover coupled with the influence of the monsoon pattern of rainfall, the fragile catchments have become prone to low water retention and high soil loss associated with runoff (Valdiya 1985, Rawat and Rawat 1994, Joshi and Negi 1995). Large-scale deforestation which occurred in the lower range, known as

Shivalik range of Himalayas during the 1960s caused the soil on the land surfaces to be directly exposd to the rains. This unprotected soil was readily removed from the land surface in the fragile Shivaliks by the combined action of rain and resulting flow (Kothyari, 1996). Most parts of the Himalayas, particularly the Shivaliks, which represent the foothills of the Himalayas in the northern and eastern Indian states, are comprised of sandstone, grits and conglomerates with the characteristics of fluvial deposits and with deep soils. These formations are geologically weak, unstable and hence highly prone to erosion. Accelerated erosion has occurred in this region due to intensive deforestation, large-scale road construction, mining and cultivation on steep slopes. Approximately 30,000 km^2 have been severely eroded in the north-eastern Himalayas due to shifting cultivation (Narayana and Ram Babu, 1983). Increased runoff during the summer monsoon rains has been transferring sediments into the streams and causing floods (Ives and Messerli, 1989). Availability of typical rocks in the particular regions also add substially to sediment load. For example, presence of clay-rich rocks, such as the Spiti shales and schists and the widespread existence of limestone deposits, lacustrine muds, and tills contribute to sediment supply to the Spiti River in greater Himalayan range. The combined effects of natural and anthropogenic instability can be visualised in widespread surface erosion processes and local mass movements. Similar erosional features have also been reported by Fort (1987) for dry continental Mustang Himalaya of Nepal.

Deforestation and associated soil erosion has caused desertification of land in the Shiwalik hills in the Hoshiyarpur district of the Punjab state. In 1852, the extent of degraded land in this area was 194 km^2, which increased to 2000 km^2 in 1939, and then to 20,000 km^2 in 1981 (Patnaik, 1981). Similarly, large tracts of cultivable land have been abandoned because of the erosion of topsoil in the Kotabagh area of the Nainital district in the state of Uttar Pradesh (Valdiya, 1985). In addition about 45% of the perennial hill springs in these areas go dry during the non monsoon season because of the reduction in groundwater storage resulting from the erosion of the pervious soil horizons (Valdiya, 1985).

High altitude glacierized basins contribute to sediment in the river very significantly. Himalayan glaciers produce a large amount of rock debris and have large lateral and terminal moraines compared with glaciers in the other part of the world. As a result moraine-dammed lakes commonly form in front of retreating glaciers. These moraine-dammed temporaray structures are unstable and a slight disturbance by seismicity or heavy rainfall can easily result in an abrupt release of stored water and rock debris (Yamada, 1993). Further, high velocity, erosive glaciers driven by high accumulation rates, steep topographic gradients, and high rates of ablation yield cause high concentrations of sediment in their meltwaters. Such glaciers are thought to be important active agents of erosion and sediment transport in regional denudation system (Gardner, 1986).

Inspite of the history of sediment measurements in the River Ganga dating back to the early 19th century when Rev. R. Everest published his report in *Royal Asiatic society*, Bengal, on (soluble and insoluble) sediment transport (Everest, 1832), measurements of discharges and sediment concentrations near the portals of the glaciers have not been continued and the country lost an early initiative on long term time series. The review of the literature shows that most of the studies in our country are carried out for the plain rivers or for some rivers in the lower part of the Himalayas. Sedimentation study for high altitude glacierized basins in the Himalayas are very limited. The same is true for the Himalayan glaciers where systematic studies are lacking. Only few studies based on the limited time period are available for few specific glaciers. These studies can not be generalized even for the near by glacier because of changes in geology and topography. In addition to assessment of sediment load from the Dokriani glacier basin, a detailed discussion on the processes associated with erosion in the glacierized basins is presented in this report.

2.0 EROSION PROCESESS

Important erosion processes causing sedimentation in the high altitude region can be classified as.

2.1 Talus Erosion

In the cold desert region fragmented material is formed by freeze-thaw action on sedimentary rocks. Distintegrated material and down slope movement of soil material into the river system, including mobile talus slopes, is common features in the high altitude regions.

2.2 Rain-induced sediment from a basin

In the lower part of the mountains heavy rain with high intensity are observed. Rainfall induced overland flow has the ability to detach and transport large amounts of sediment and depends mainly on ground slope, soil characteristics, vegetation cover, and conservation practices. These factors may vary in space significantly even for small catchments. Sediment is detached by raindrop impact and surface runoff. Under such conditions rain splash erosion becomes common and sediments find their way into gullies and streams. Rain-induced overland flow has the ability to detach and transport large amounts of sediment and depends mainly on ground slope, soil characteristics, vegetation cover, and conservation practices. These factors may vary in space significantly even for small catchments.

Sediment particles are diverted to the drainage zone, where they can be accumulated or depleted according to flow conditions in the channel reach. High suspended sediment concentrations may also arise from the transport of sediment to the fluvial system during rainfall events. The heaviest rainfall events wash fine sediment into the fluvial system and generate high river flows (Hodson, 1994). In the absence of rains, there is very little splash erosion in the cold desert region.

2.3 Laminar erosion by snow melt

In the high altitude regions where snow is experienced during winter, melting takes place in the summer period. Melting of snow takes place continuously during summer period and makes water available over the ground surface for longer period. Consequently, soil below the snowpack becomes fully saturated and suffers from laminar erosion with snow melt water.

2.4 Gully erosion

As the runoff water begins to accumulate in rills, which are gradually developed into gullies, process of soil erosion takes place. Gully erosion is an important source of sediment in the river system as the eroded soil has little chance of being retained in the gully bed owing to turbulent water on steep slopes. In the hilly areas, the eroded sediment immediately enters the stream network due to high topographical gradients and takes it further course. At some locations, steep or even perpendicular, gully sides are indicative of regular activity in the Himalayan region. The presence of pinnacles along the gully sides and bottoms is common in Spiti and at places in Kinnaur region of Himalayas. These forms are associated with difficult soils, which are highly erodible. The height of these pinnacles from the adjacent ground itself gives an indication of the extent of sediment transport that the surrounding land has suffered.

2.5 Stream and river bank erosion

Many of the rivulets and streams in the lower mountainous areas show the meandering pattern. Therefore, large quantities of sediments are brought into the streams with frequent toe cutting and resulting slope failures. Large amounts of sediment enter the main rivers due to bank slumping. The problem is very acute in those areas with loose strata. Much material also enters the main streams as a result of river erosion of loose glacial and colluvial deposits. The large pinnacles on the banks of the Spiti River indicate the extent of such erosion losses.

2.6 Road construction erosion

In general, roads are the major means of transportation in the mountains and specially in the Himalayan region. In most cases the roads are built along the river courses. Unfortunately, such construction in this mountainous terrain, in contrast to the plains, requires much blasting. The whole process has led to large-scale instability and large amounts of debris are pushed indiscriminately into the rivers. Sharma (1987) reported that the sediment load from road cutting in the Himalaya is as high as 8,000 m^3 km^{-1}. In general, no steps are taken to stabilize cut and fill slopes. As much as 2 t of sediment are reported to be generated each year by each 10 m length of road in the Himalaya (Narayana and Rambabu, 1983). Debris falling onto the highways from landslides and slips finds its way into streams, thus increasing their sediment load. Thus, road construction establishes a source of permanent augmentation of siltation in the rivers, which becomes very active during rainfall or snow melt period. .

2.7 Landslides

Landslides and slips are very common features in the mountains, specially during rain events, and becomes a major sources of sediment in the river system. Besides the anthropogenic intervention, the nature and structure of materials involved also promotes a high incidence of landslide activity. Thin beds of clayey limestones, shales, highly jointed sedimentary beds and schists are especially susceptible. The accompanying geological structures, including steep dips, folds, and faults, further influence the occurrence of landslides. A high frequency and intensity of seismic activity increases the landslides significantly..

Landslides are the other dominant cause of soil erosion and related problems in the Himalayas. In India landslides mainly occur along the Shiwaliks and middle Himalayan ranges. The landslide prone areas also coincide with the locations of high magnitude earthquakes, geological faults and values of the rainfall event ratio (E) which indicate the occurrence of intensive rainfall for long duration.

2.8 Glacier erosion

A high quantity of sediment is transported from the glacierized basins. Glacial erosion is very widespread. The movement of a large mass of ice down slope is accompanied by large amounts of sediment due to glacier bed erosion. Further, thousands of tons of debris is bought down by a glacier and dumped near the snout of glacier. This debris serves as a major source of siltation Additional hazards are the flash floods, due to heavy snow melt and ice melt, glacier-dammed lake outburst etc. Under such events a high amount of debris is transported into the melt water runoff. In the Himalayan region, there are many conspicuous glacier paths devoid of vegetation that directly dump debris into the river beds.

3.0 EFFECT OF SEDIMENTATION ON RESERVOIRS

A large number of dams have been constructed in India since independence for hydroelectric power generation, domestic water supply, irrigation, flood mitigation etc. Most of these reservoirs have been designed for a life period of 100 years, but excessive siltation from accelerated erosion due to human interference is threatening to reduce the live capacity of these reservoirs. The useful life and capacity of reservoirs are being depleted faster than planned because of increasing soil erosion in their catchments. Annual sediment inflow into many of the reservoirs in India varies from 0.6-122.7 ha m/100 km^2 (0.8-172 ton/ha) of the catchment (Dos et al.,1969), and except for a few well protected catchments, others are producing much higher yields than the 5.7-6.9 ha m indicated by Khosla (1951). Deposition in the reservoirs can be decreased only with implementation of soil conservation measures in their catchments. Narayana and Ram Babu (1983) estimated the magnitude of total soil erosion taking place in India. This was computed on the basis of various soil loss studies from different land units and land uses, reservoir sedimentation data, and river sediment discharges. It was reported that on the country scale approximately 5, 334 × 10^6 tons of soil (1,640 tons/km^2) is being annually eroded. The country's rivers carry an approximate quantity of 2,052 × 10^6 tons (626 t /km^2). Of this, nearly 480 × 10^6 tonnes is deposited in various reservoirs and 1,572 × 10^6 tons are washed into the sea every year. In other words, about 29% of the total eroded soil is permanently lost to the sea, 10% is deposited in reservoirs resulting in loss of storage capacity of 1%-2% per year, and 61% of eroded soil is being transported from one place to another. Although these rates are approximations, soil erosion is serious and integrated measures of soil erosion control are needed.

The natural rates of denudation in Himalayas have also been reported high (Rawat and Rawat 1994). The fragile ecosystem of Himalayas has been an increasing cause of concern to environmentalists and water resources planners. The steep slopes in the Himalayas along with depleted forest cover, as well as high seismicity have been major factors in soil erosion and sedimentation in river reaches (Varshney et al. 1986). In order to reduce rate of the siltation of the reservoirs, soil and water conservation measures are now a major component of all operating river valley schemes. Prediction of sediment yield is a necessity if adequate provision is to be made in the design of conservation structures to offset the ill effects of sedimentation during their life time.

Analysis of the sedimentation data (Murthi, 1977; Shangle, 1991) indicate a wide range of sedimentation rates in these reservoirs. For example, for some large reservoirs, such as the 2.4 × 10^9 m^3 Ram Ganga reservoir in UP, the data indicate a very small rate of sedimentation, while the 3.1 × 10^9 m^3 Srirama Sagar reservoir in Andhra Pradesh was found to have lost 25% of its capacity during the first 14 years of impounding. Table 1 provides a compilation of the reservoir sedimentation rates estimated by various investigators. Based on a screening analysis of the available data, Morris (1995) concluded that few reservoirs in India have lost as much as 50% of their capacity to date. By 2020 it was expected that 27 of the 116 reservoirs will have lost half their original capacity and by the year 2500, only about 20% of India's existing reservoirs will have lost 50% of their capacity.

Table 1: Reservoir sedimentation rates in India (Morris, 1995).

Reservoir	River Basin	Year of construction	Catchment area (km^2)	Reservoir volume (mm)	Sedimentation rate (mmYr^{-1})	50% capacity lost (Yr.)	Life of reservoir (Yrs.)
Srirama Sagar	Godavari	1970	91,750	35	0.62	1998	56
Nizam Sagar	Godavari	1930	21,694	39	0.64	1960	61
Matatila	Betwa	1956	20,720	55	0.44	2018	124
Hirakud	Mahanadi	1956	83,395	97	0.66	2030	147
Girna	Girna	1965	4,729	129	0.80	2045	161
Tungabhadra	Krishna	1953	28,179	133	1.01	2019	132
Panchet Hill	Damodar	1956	10,966	137	1.05	2021	130
Bhakra	Satluj	1958	56,980	172	0.60	2101	287
Maithon	Damodar	1955	6,294	218	1.43	2031	152
Lower Bhavani	Bhavani	1953	4,200	222	0.44	2205	504
Mayurakshi	Mayurkashi	1954	1,860	327	1.63	2054	201
Gandhisagar	Chambal	1960	23,025	336	0.96	2135	350
Koyna Dam	Krishna	1961	776	3851	1.52	3228	2533

4.0 ESTIMATION OF SOIL EROSION

Information on soil erosion is needed for planning and the design of soil conservation measures. Such information can be obtained through actual measurement and also through the use of estimation procedures. Measurement of suspended sediment continuously and evaluation of the true amount of suspended sediment in torrent streams is very difficult. Several methods exist for the measurement of soil loss from different land units including the measurement from runoff plots of various sizes for each single land type and land use, small unit source watersheds and large watersheds of mixed land use. In mountainous areas, size of suspended particles varies considerably with hydraulic conditions, turbulence, velocity, gradient, transport capacity and other stream features.

Surveys for determination of soil erosion rates from catchments and deposition rates in reservoirs are frequently conducted by the various governmental agencies in India (ICAR 1984; and CBIP 1981). Measurements of sediment load are made in many rivers across the country by other governmental agencies (CS&WC, 1991; Shangle, 1991). Nevertheless, sediment loads remain ungauged for the majority of the streams, because of the lack of funds. However, the other hydrological data, such as rainfall and runoff, are available for the majority of rivers basins. Estimation procedures can be therefore used to estimate erosion rates for such catchments. In India Joglekar (1965) and Varsheney (1975) have suggested a number of enveloping curves for the prediction of sediment yield for different catchment areas. Corrrelation studies conducted by Jose and Das (1982) revealed that area alone does not have any significant association with sediment production rate (SPR) and hence there is scope for multivariate analysis using climatic and physiographic parameters. Statistical models on a spatially distributed basis have been developed by Mishra and Satyanarayan (1991) and Bundela et al. (1995) for small watersheds in river Damodar in east India.

Several equations are also available to estimate soil erosion. The universal soil loss equation (USLE), developed by Wischmeier and Smith (1978), is one of the most useful and reflects considerable research data. The USLE, an empirical equation, estimates average annual mass of soil loss per unit area as a function of most major factors affecting sheet and rill erosion. This equation is written as

$$A = RKSLCP$$

where A is soil loss per unit area, expressed in units selected for K and for the period selected for R; in practice, the units are usually selected so that A is computed in tons per acre per year, but other units can also be selected. R is the rainfall-runoff factor- the number of rainfall-erosion index units, plus a factor for runoff from snow melt or applied water where such runoff is significant. K is erodibility factor-the soil loss rate per erosion index unit for a specified soil as measured on a unit plot, L is slope length factor- the ratio of soil loss from the field slope length, S is the slope steepness factor, C is crop management factor and P is the support practice factor. The USLE gives estimate of total soil detached and displaced over short distances, but do not indicate the sediment delivered to the reservoir. Much deposition and reduction in sediment yield occurs between the sediment source and reservoirs. This reduction is estimated with a sediment delivery ratio. Sedimentation in reservoirs defined by trap efficiency, depends on factors such as the ratio of runoff inflow to reservoir capacity, sediment size, shape and stage of the reservoir, outlet works, and methods of reservoir operation. In India, reservoir sedimentation is estimated from the suspended load of the stream feeding the reservoirs, and by periodic direct measurement of sediment deposition in reservoirs.

An isoerodent map of India has been produced based on the erosion index values (Babu,R., et al., 1978), which shows the potential erositivity of rainfall (Singh et al., 1990). Methods have also been evolved for determination of the off site deposition of eroded soil and the sediment yield from large catchments (Garde and Kothyari, 1987; Narayana and Ram Babu, 1983; Kothyari et al., 1994). However, the most detailed study to date for estimation of sediment yield from large catchments is the work of Garde and Kothyari (1987) (Figure 1). An analysis of the data from 50 catchments with areas ranging from 43 km^2 to 83,880 km^2 produced the following equation for mean annual sediment yield

$$S_{am} = C\, P^{0.6} F_e^{1.7} S^{0.25} D_d^{0.10} (P_{max}/P)^{0.19}$$

where

$$F_e = (0.8\, F_A + 0.6 F_G + 0.3\, F_F + 0.1 F_W)/A$$

here S_{am} is the mean annual sediment yield in cm, C is a coefficient depending on the geographical location of the catchment, P is the average annual rainfall in cm, S is the land slope, D_d is the drainage density in km^{-2} P_{max} is the average maximum monthly rainfall in cm and A is the catchment area in km^2. F_e is defined as the erosion factor and F_A is the area of arable land in the catchment, F_G is the area occupied by grass and shrub while F_W is the area of waste land and F_F is the forested area.

The data from 154 catchments in India concerning the variables on the right hand side of equation (1) were also used by Garde and Kothyari (1987) to produce an iso-erosion rate map of India. The iso-erosion rate map showed that mean annual erosion rates in India vary from

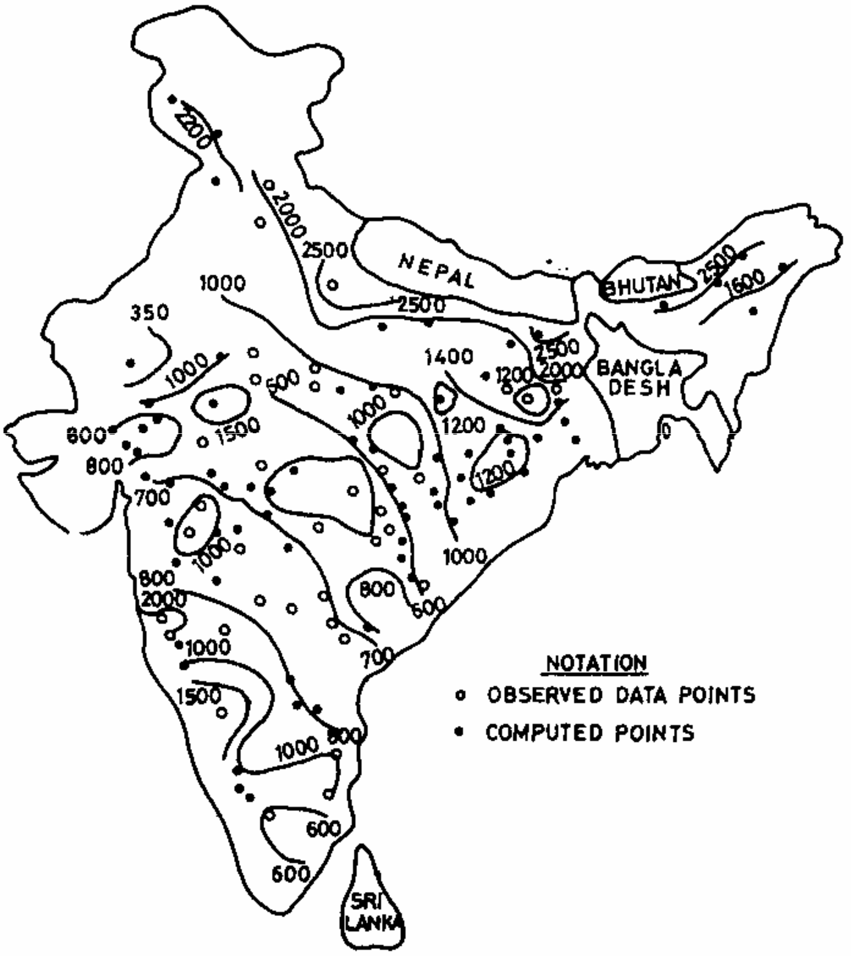

Figure 1 Erosion rates in India. The iso erosion lines refer to annual erosion rates in tkm^{-2} year^{-1}(based on Garde & Kothyari, 1987)

350t km^{-2} $year^{-1}$ to 2500 t km^{-2} yr^{-1}. High erosion rate values, as found in the northeastern region, parts of Punjab, U.P. and Bihar and in certain areas of Andhra Pradesh can be attributed partly to the higher rainfalls in these regions and partly to the geologic conditions and land use. Considering the fact that out of the variables affecting the erosion rate, as indicated by equation 1, only the rainfall variable changes from year to year: the following equation has been proposed for the estimation of annual erosion rates from catchments (Garde and Kothyari, 1987).

$$S_a = C\, F_e^{1.7}\, S^{0.25}\, D_d^{0.10}\, (P_{max}/P)\, P_a^{m} \tag{3}$$

here S_a is the annual erosion rate in cm, P_a is annual rainfall in cm and m is the exponent. The value of m is related to the coefficient of variation of annual rainfall as per Figure 2.

Various modelling approaches have been developed in the past. Hrissanthou (1986) presented a mathematical model to estimate the sediment yield from a large basin on a daily basis. The basin was divided into 85 sub-areas of 5 km × 5 km grid. The soil detachment in each sub-area was computed by using USLE. The resulting predictions were relatively satisfactory considering the large basin area. Keeping in view the physical principles in computing the sediment delivery in a catchment, Dickinson et al. (1986) developed a procedure for the evaluation of spatially distributed sediment delivery ratios. The development of drainage networks over a bare slope was analysed by Roth et al. (1989). The basic equations of water continuity, sediment continuity and momentum conservation were used to describe the movement of water and sediment.

The subdivision of the drainage area into small homogeneous units covering a few hectares is a tedious and time consuming procedure when applied to medium or large watersheds. To overcome these problems, in recent years cell based distributed models have been the subject of several applications. Recent developments in the modelling of the Earth's surface through raster digital elevation models (DEM) have become the basis for new approaches in hydrological modelling. Bemporad et al. (1995) modelled hydrosedimentological phenomena at a cell scale to analyse the sediment yield. This approach has been used to get the information that in which regions of the catchment erosion was higher as well as in which regions accumulation was more likely to occur. This is an obvious advantage with respect to conventional lumped approaches, where only the total amount of sediment produced at the catchment outlet can usually be estimated.

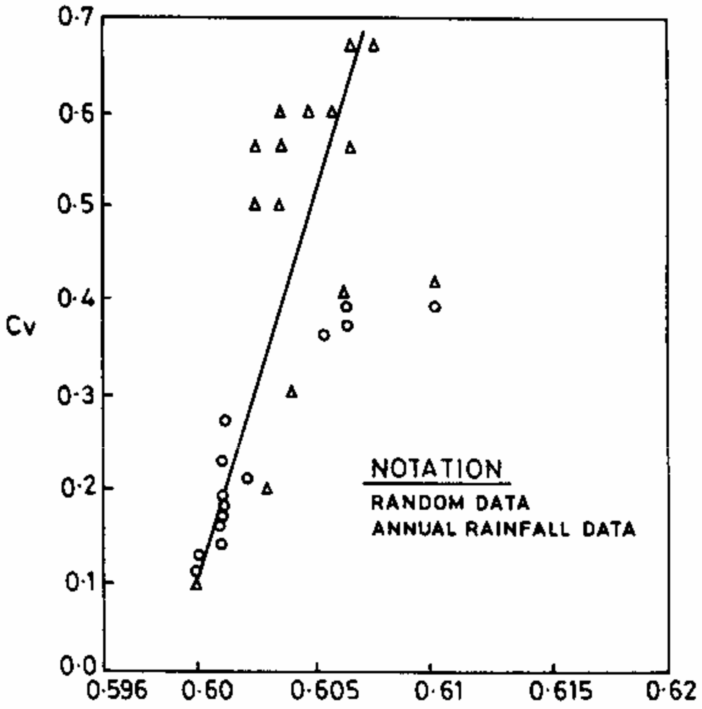

Figure 2 Variation of m with C_V (based on Garde & Kothyari 1987)

5.0 REMEDIAL MEASURES

Soil erosion and deposition are worldwide problems and not restricted to India. However for sustainable development it will be essential to thoroughly understand and solve these problems. For this purpose, a detailed screening analysis should first be carried out to identify areas of severe erosion and sedimentation. A greater number of streams will have to be gauged to determine their sediment loads. Also, detailed reservoir surveys will have to be carried out for determining sediment deposition. Next, priority catchments and reservoirs may be selected for experimentation to study the effectiveness of soil conservation measures and reservoir operation policies. Finally the technology thus developed for sediment management could be transferred by expanding these sediment management activities to the other catchments and reservoirs.

Various programmes for soil conservation are currently receiving high priority in India. However, it seems to be a difficult task to control erosion over vast tracts of lands by soil conservation practices alone. Nevertheless, the problem of reservoir sedimentation can be brought under control by construction of upstream sediment traps and by evolving effective procedures for sediment routing and sediment removal from existing reservoirs. Promoting vegetation and construction of check dams are some of the measures recommended for controlling soil erosion and for reducing the sediment yield from arid zone drainage basins. Government sponsor large scale soil conservation programmes and watershed management strategies, involving the promotion of vegetation on the slopes within the drainage basins and engineering measures such as check dams, have caused significant reductions in sediment yield throughout the Indian arid zone. The qualitative effects of plant cover in reducing sediment yield through deposition of sediment in the drainage basin, due to increase resistance to flow and reduction in flow velocity are well known (Rodda, 1976). Sediment yield was reduced by between 65 and 94% in different physiographic regions by preserving vegetation on the slopes within the drainage basins (Table 2). The reduction in sediment yield shows a positive correlation with the vegetation cover, which varies between 3 and 6%. Elwell (1981) observed that sediment yield decreased exponentially with increasing vegetation cover. The reduction in sediment yield was only between 33 and 60% for the coarser fractions (>0.05 mm) in similar physiographic and rainfall zones. Thus, the sediment generated is finer in the drainage basins with good vegetation cover.

Table 2: The effect of vegetation cover on sediment yield

Physiographic region	Estimated vegetation Cover (%)	Sediment yield without vegetation ($m^3km^{-2}yr^{-1}$)	Sediment yield with vegetation ($m^3km^{-2}yr^{-1}$)
Sandy plain	4	360	60
Dune complex	3	230	80
Younger alluvial plain	6	890	50
Older alluvial plain	3	520	120

From the drainage basins influenced by biotic activity, check dams reduced the sediment yield by 71% from the older alluvium and shale formations under similar rainfall and drainage basin characteristics (Table 3). This reduction is due to the deposition of the coarser fractions within the impoundments as a result of the reduction in the flow velocity in passing through the check dam.

Table 3: The effect of check dams on sediment yield

Physiographic region	Sediment yield Without check Dams ($m^3km^{-2}yr^{-1}$)	Sediment yield with check dams ($m^3km^{-2}yr^{-1}$)
Older alluvial plain	1660	480
Rocky/Gravelly piedmont	420	120

The management of sediment in a natural watershed involves the transformation of physical inputs into outputs in conformity with deterministic physical laws, the analysis of stochastic factors which govern sediment phenomena and the consideration of social and economic factors (Bruk, 1992). Deterministic analysis of sedimentation and erosion processes usually requires the prediction of spatially variable hydrological processes at fine resolution. In fact, the use of input output approaches to provide a linkage between the erosion estimates and the observed sediment measurements at the catchment outlet may not always be correct, as sediment may accumulate inside the catchment and be removed at later times.

Land-use practices have a decisive role in soil and water conservation, particularly in the mountains (Ives and Messerly 1989, Dunne et al. 1991). Several studies focussing on soil erosion and water yield have emphasised the role of an effective vegetation cover, which dissipates much of the raindrop energy and promotes high rates of infiltration (Sorriso-Valvo et al. 1995, Oyarzun and Pena 1995). This preliminary study warrants planting the wasteland with multipurpose tree species which could yield fodder, firewood and other products for subsistence (Nautiyal and Negi 1994) and to ensure soil and water conservation in this region.

6.0 FACTORS CONTROLLING THE SUSPENDED SEDIENT INTO GLACIER FED RIVERS

Based on the survey of sediment yield from 1358 drainage basins with an area ranging from 350 to 100,000 km^2, Jansson (1988) reported that within particular climatic zones where glaciers are active, sediment yield tends to be higher. Harbor and Warburton (1992) also reported that rates of erosion typically are higher for glacial than non-glacial processes and, therefore, sediment yields are higher in glacial rivers than in comparable rivers not fed by glaciers. For example, Embleton and King (1975) have observed a five fold difference in sediment yield between the glacial Hoffellsjokull river in Iceland and a nearby non glacier fed river as evidence that glacial abrasion provides more material for stream transport than do the non glacial weathering processes. A number of studies have demonstrated that specific sediment yield may increase downstream, due to remobilisation of sediments pushed by the active glaciers (Ferguson, 1984; Warburton, 1990). The main factors controlling the sediment into glacier melt rivers are discussed in detail in the following section.

6.1 Rain-induced sedimentation

The water runoff caused by precipitation and glacier meltwaters contribute to rapid runoff and natural erosion. Many studies have stressed on the importance of precipitation on sediment yield from glacial basins. Rainfall in the glacierized basin helps to increase sediment from different sources. When rainfall occurs in the glacierized basins, debris and moraines present over the glacier surface contribute significantly to sediment load of the melt stream. The loose soil available on the steep side walls of the valley is eroded during rain events. Slumping from unstable moraines under rainy conditions causes sudden increases in sedimentation concentration. A similar process can often be observed on river banks, where erosion and removal of fine sediments cause the whole bank or part of it to slump into the water. As sediments in moraines tend to be very poorly sorted, the reason for the erratic changes in grain size distribution could be found. It has been estimated that when heavy rains double the water flow, scouring capacity is increased 4 times, carrying capacity 32 times and the size of the particles carried 64 times (Tempany and Grist, 1958).

The most important adverse effect of a cloudburst in the mountainous areas is the triggering of large-scale mass movements, which introduce enormous amounts of sediment into the drainage system(Carson, 1985). The consequenses of large-scale erosion due to a cloudburst in small catchments is two ways- i) the excessive sediment load may cause aggradation conditions of the riverbed further downstream, thereby increasing the water level in general and flood hazards in particular (Pal and Bagchi, 1975) and ii) the debris including big boulders resulting from the sudden and-scale erosion may temporarily dam the river. Any subsequent breaching may cause a devastating surge of water, leading to excessive mass movements along its course and causing widespread damage to life and property.

Gully erosion is one of the major environmental hazards in the Himalayas. During cloudbursts, the gully erosion often has devastating effects in the form of debris flow and landslide dams. Gullies are long, narrow, and deep channels, usually having steep gradients ($>60^0$). Water flows through these channels, which generally have a small catchment only during rains. During cloud burst events, the surface runoff water is excessive and continuous. Therefore, top layer of soil or debris below oversaturates, leading to a shallow perched water table rising up to the surface. This reduces the grain-to grain or block-to-block contact to the slope material below. Such conditions may often lead to failures of the slopes. Under extreme conditions, it may result in debris or soil flow. The debris flow of colluvium or torrent deposit along the gullies takes place at a tremendous velocity, ranging between 1 and 10 m/sec (Deoja et al., 1991). Moreover the viscosity of water increases rapidly (Bevarage and Culbertson 1964). Because of the increased velocity and viscosity of the water, the capacity to carry heavy boulders increases many times. The maximum size of the boulders that can be transported by this abnormal drag force is in the order of 1.8 m (Deoja et al.,1991). The flow of debris may be arrested in a narrow valley, due to the big boulders, and lead to a landslide dam. The impoundment of rainwater behind such a dam may cause floods upstream, while its breaching may lead to flash floods downstream. The stability of these dams depends on a number of factors such as the volume, texture, sorting of the dam materials, capacity of storage, nature of seepage water, rate of sedimentation, and amount of water flow into the lake. Depending on such conditions, these dams may be breached from within a few hours to up to a few years. However, if the dam is formed within the gully itself then, due to the very limited storage available, it often is breached within a few hours, resulting in flash floods and large-scale devastation in the form of loss of life and the triggering of landslides. Anbalgan (1996) has discussed a disastrous events triggered by the cloudburst in July 1983 in Kumaun region of Himalayas.

A substantial fraction of the annual total sediment load is transported during rain-induced flood events or subglacial blocking events due to abrupt dislocations of subglacial flow nets and supply of sediment in addition to that derived from the glacier sub-sole. Greatly enhanced suspended sediment content occurs during floods resulting from the emptying of ice-dammed lakes (Collins, 1979b) when water pressure and ice sliding velocity are increased .

6.2 Subglacial sediment supply and delivery to melt waters

In the basins which experience only seasonal snow and there are no glaciers in the basin, sediment load is relatively less as compared to glacierized basins. In the case of seasonal snowpack melting, the melt water produced on the snow surface during summer first infiltrates the snow mass and then discharges into a river channel as subsurface flow (Kobayashi, 1986). The subsurface flow could then produce the sediment discharge by eroding soil grains or the underlying bedrock debris in the porous media (Kurashige, 1993). Alternatively the river flow generates the sediment discharge by eroding soil grains and bedrock fragments deposited on side gorge slopes, together with bed materials (Chikita, 1993). In order to develop a physical model of snowmelt discharge including sediment transport from a drainage basin, both the mechanisms of snowmelt discharge and sediment transport should be clarified. Chikita (1993) compared the suspended sediment discharge from a snow-covered drainage basin (Ikushunbetsu river, Japan) with a glacier covered basin (Peyto creek, Canada). One of the common features in both rivers was that the suspended sediment consists of more than 90% of silt and clay, and the sediment concentration of water varied diurnally in phase with water discharge. Chikita (1996) studied the mechanism of river sediment discharge from snowmelt by observing meteorological and hydrological conditions, and by identifying the source of suspended sediment.

In the glacierized areas, sediment is produced by glacial erosion processes over wide areas of bed throughout the year, whereas melt water flow with sufficient velocity and turbulence to maintain traction and suspension of fine particles is restricted to the ablation season and spatially to passageways constituting the basal drainage system. It is unlikely that sediment would continue to accumulate in particular areas of bed either from year to year or during an ablation season. Debris will be removed by migration of subglacial channels over wide areas of the bed during summer, or by a network of small passageways with high enough flow, which covers a large proportion of the sub-sole in the ablation season. During highest diurnal discharges in late afternoon, the rate of sediment supply fails, to maintain concentration in increasing volumes of flow, suggesting that increased shear stress at conduit margins is offset by increased volume-wetted perimeter ratios. Disproportionate increases in flow volumes in channels incised in bedrock over those in smaller conduits, or stable sedimentary margins to conduits, would account for decreased sediment concentrations at high discharges. However, low flow sediment contributions and rapid variations of concentration point to conduit margin instability, and suggest a flow related reduction in the rate of sediment supply. Increased water pressure during high discharge may lessen the amount of deformation of basal sediments into conduits and some water may be forced into bank storage in basal moraine, to be returned later, during lower discharges, aiding collapse of conduit margins. Superimposed on this basic flow related pattern, sudden conduit course migrations, possibly initiated by blocking of conduits by sediments, integrate unworked zones of sediment with water flow.

Sediment transport to the portal in a period of time will be supply-related in effect, through what size of area of unworked glacier sole and subsole becomes integrated with flow, and how much sediment is held there. The latter will presumably be influenced by the length of time elapsed since melt water previously covered an area. How much sediment is available will also depend on the thickness and debris content of the basal ice layer, and whether there is bedrock or an unconsolidated, deforming debris sub sole. Areal integration of sub sole with flowing melt water will depend on the type of basal passageway system and how the system develops in response to changes in water pressure arising from seasonal and diurnal variations of surface-water input. Continued expansion of the network over wider areas of the bed permitted continuing contact with zones of sediment throughout the drainage event. Frictional melting of ice from the margins of basal conduits deforming inwards under ice-overburden pressure provides a small but continuing debris supply to melt waters in channels incised up into ice or down into bedrock. Some fine debris will be derived from wear of bedrock by flowing melt waters charged with sediment, particularly within incised channels. Fine sediment is readily washed out from basal zones in contact with flowing melt water. Ostrem (1975) and Drewry (1986) have suggested that whereas actual glacial erosion may be accomplished uniformly and steadily, the evacuation of sediments from a glacier depends very much on the amount of water draining through the glacier. This partly substantiates (Embleton and King, 1975) findings that sediment yields from beneath ice sheets in Arctic areas are lower than yields from temperate glaciers, since the cold in the Arctic allows for little runoff to flush sediments from the glaciers. The relative potency of glacial and nonglacial sediment transfer varies, depending on climate, topography and geology.

The bulk of sediment delivery probably results from glacier sliding. Sediment will be released to melt waters in the basal hydrological system by melting of debris rich basal ice from the glacier sole, and by deformation of basal sediment into passageways through glacier sliding. Migration of channels *en masse* with sliding ice, and movement of channels relative to surrounding ice by melting of channel margins, may allow melt waters to impinge on patches of basal sediment. These interactions will be more effective if the orientation of the conduit system is more transverse to the direction of sliding. A dense network of small conduits arranged at an angle to the direction of glacier flow would be expected to gather more sediment than a few larger conduits with alignment parallel with flow. The theoretical water pressure discharge relationship for conduits suggests that larger conduits develop at the expense of smaller ones (Rothlisberger, 1972). Development of the conduit system in this way would form a plausible explanation of the decline in sediment flux with progression of the ablation season. Variations in sliding velocity from day to day, together with changes in conduit dimensions with discharge through-put which alter the area of debris in contact with flowing water, will also influence sediment load. Sediment supply will be favoured in conduits, which respond to increased flow by enlarging cross- sectional areas through widening over the bed (and hence decreasing the width depth ratio), rather than growing as cylindrical tubes in surrounding ice.

Enhanced sliding also appears to be associated with high pressure in distributed basal drainage systems consisting of many small conduits or of a network of linked cavities localized by topographic features of the bed (Humphrey et al., 1986; Iken and Bindschadler, 1986). Expansion of cavities enlarges the area of melt water in contact with basal ice and sub sole debris. Abrasion rates increased by enhanced sliding may generate additional fine sediment. High subglacial water pressure and sliding events in Alpine glaciers occur in the early part of the melt season (Iken and Bindschadler, 1986). How the subglacial drainage network becomes established, and how the system subsequently evolves through the ablation season, are both influenced by occurrences of high water pressure events as well as by seasonal patterns of hydrometeorological conditions.

Humphrey and Raymond (1994) reported that no precise relationship was found between the timings the ice slow-downs and the peak release of water. Correlation was also lacking between peak velocity and water discharge. In general, the water discharge and sediment concentration start to rise several hours before the ice slow down, but the high water and sediment fluxes are not consistently related to the slow-down itself. Two possible interpretations are explored: (1) It is understood that slow-down events are mechanically related to the release of water starting before the slow-down, and within a few hours the water reaches at the outlet of the glacier. The water and sediment are directly related to the high sliding velocities, not the slow-downs, and the lag time of the basal flow system is 12-24h.

6.3 Sediment flux and subglacial drainage network

Patterns of suspended sediment flux during ablation seasons provide an indirect insight into the evolution of the subglacial drainage system. Thus measurements of temporal variation in suspended sediment concentration and discharge of melt waters emerging from the portal can provide information concerning the interaction of flowing melt water with sediment beneath a glacier. Re-organisation of channels, and relocation of passage ways making up the basal hydrological network with respect to the bed, result in the evacuation of large quantities of fine sediment in portal melt streams. Collins (1979a) attempted to examine those interactions between melt waters and sedimentary material at the sole of an Alpine glacier which are indicated by variations in water and sediment outflow from the terminus. Based on observations at several glaciers, seasonal interaction between the developing basal drainage network and subglacial sediment delivery to melt waters has suggested that the concentration of silt is generally lower towards the end of summer than at the beginning (Ostrem et al., 1967).

There are sudden perturbations in the spatial stability of subglacial drainage systems, which result in sediment delivery events. These subglacial hydrological events tend to occur during periods of increasing flow, and are more easily discerned during the first part of the melt season, before the maximum discharge of the summer. The events indicate that melt water spreads out over the glacier bed at times of increasing water pressure, and suggest that diffuse flow in linked cavities probably occurs over wide areas of sub sole, particularly at the start of the melt season. Susbstantial partial areas of the basal drainage system undergo concerted re-organisation during events, which persist for one or several days. Whether this corresponds to collapse of a linked cavity to a major conduit system and whether the changed network structure persists subsequently are not clear. Sequences of events during the early season indicate successive integration of partial areas of sub sole with flow.

This interpretation of total daily sediment flux in terms of development of the subglacial drainage network has implications for the understanding and modelling of the continuously changing relationship between sediment concentration in melt waters and discharge from glacier portals. Investigation of diurnal variations in that relationship should also provide more detailed information about the nature of subglacial hydrological events. While measurement of sediment flux in melt water can provide much information about interactions of the subglacial drainage system with glacier sub sole, combined observations of these variables together with water level variations in bore holes, short term fluctuations of glacier sliding, and other water quality indicators would usefully identify which basal areas are involved in particular events, and would provide more detail of the nature and behaviour of basal hydrological networks.

7.0 OBSERVATIONS

There are very few observations on sediments near the tongues of glaciers (Davydov 1967, Sadykov 1976, Krenke and Suslov 1980), but there are more measurments of suspended sediment concentration and sediment discharge at river gauges located down-river at some distance from the glacier tongues. Reduction of sediment transport in run-off down mountain rivers is not significant due to the high velocity of flow. Measurements of the quantities of suspended sediments and solutes evacuated from partly glacier covered catchments provide means of estimating gross rates of denudational lowering by glacial erosion (Ostrem, 1975) and chemical weathering (Reynolds and Johnson, 1972), and of identifying the relative significance of various subglacial processes (Vivian and Zumstein, 1973). Observation of the quality of water draining from glacier snouts permits investigation of the nature of erosional processes integrated over large areas of glacier bed, effectively sampled by flowing melt waters which acquire their characteristics during passage beneath the glacier. Ostrem (1975) suggested that close interval sampling of melt water quality characteristics should allow interpretation of subglacial interactions of water flow and erosional sediment supply. Using measurements of sediment concentration and discharge every few hours throughout 24 hour periods, Liestol (1967) demonstrated that melt streams beneath Storbreen, Norway, frequently changed course. Since it is unlikely that the rate of sediment production by erosion equals the rate of sediment transport by melt waters, expressed per unit area of glacier bed, accurate estimation of the rate of glacial erosion requires detailed close-interval samples of sediment concentration in melt waters over many annual cycles of discharge. However, direct observations in natural cavities at glacier beds and remote sensing of basal conditions through bore holes have provided considerable insight into the nature of erosional processes, but the processes by which sedimentary materials are transferred from sites of origin at the ice bedrock interface to melt water streams beneath glaciers remain largely unknown. Supply of sediment to the hydrological system from sites of production by erosion over wide areas of the glacier bed is probably achieved through smaller unstable conduits tributary to the arterial network.

There are limited observations on sediments near the tongues of glaciers in comparison to the measurments of suspended sediment concentration and sediment discharge at river gauges located down-river at some distance from the glacier tongues. Reduction of sediment transport in run-off down mountain rivers is controlled by the velocity and turbulence of the flowing water. Many estimates of glacial erosion have been inferred from sediment transport in glacial streams. In Norway, for five glacier basins the mean erosion rate have been observed in the range of 0.073 - 0.610 mm yr^{-1}, with 0.276 mm yr^{-1} as the mean value (Drewry, 1986). Through the assessment of sediment load transport of tapped subglacial streams in the central Alps during 10 years, the erosion rate has been estimated to be in the range of 0.97-1.13 mm yr^{-1} (Bezinge et al., 1989). Based on 4 years observations for a Himalayan glacier, Singh and Kumar (2000) reported the sediment erosion of about 2.0 mm for the whole melt period (June-September). An accurate assessment of the sediment load coming only from the glacier bed is difficult because surrounding unconvered slopes and lateral moraines contribute to the sediment being observed. Subaerial erosion rates in rock cliffs above glaciers explains readily why large values of load transport are found in the Alps than in Norway.

7.1 Suspended-sediment transport

Usually, temporal variation in the evacuation of sediment from beneath a glacier is extremely irregular. Diurnal ranges of suspended-sediment transport were variable and values fluctuated by over 100% in only one or two hour periods (Collins, 1979b).

Since basal moraine may consist of material incorporated in ice and as layers between ice and bedrock, relative movement of ice by sliding and channels by melting of their walls during expansion and migration provides sediments to the smaller subglacial streams by changing contact zones. The thick basal layer of sediments under a glacier would provide a reservoir of sediment for supply to streams.

7.1.1 Effects due to surges and seismicity on sedimentation

Sediment content of melt water is very high during the surge of a glacier (Kamb et al. 1985). The geological effect of surging glaciers is much greater than that of ordinary ones. This fact depends on several causes, namely, (i) the glacier cuts up its rock sides, especially stone screes while it surges; (ii) the glacier slides over its bed as a whole body while it surges; (iii) weathering and mechanical destruction of rocks also increase because of the changing regime of a surging glacier; (iv) moraine material is carried down the glacier much more quickly during a surge; (v) debris accumulates at the lower part of a glacier after a surge during the degradation period and then is washed away by melt water; (vi) the largest sediment run-off takes place when the lake created by an ice dam bursts out, which is usual during a glacier surge. From recent studies, it is known that there are many surging glaciers in nearly all Pamir watersheds. Surges happen everywhere in the Pamir and this is one of the factors influencing the flow of solid matter and making it very large.

Glacier surges also increase sediment discharge though their influence upon sediment concentration has not been sufficiently studied so far. The sediment runoff before and after a surge was measured on the Koksu river, which runs from lednik Abramova in Alayskiy Khrebet (Akbarov and others 1979). The accelerated flow of ice was observed on the glacier in summer

1971; in April 1972, at a time of the year when glacier rivers are usually clear and have almost no suspended sediments, the water of the Koksu river was full of mud. The main phase of the surge took place in October 1972, and the largest run-off was observed in 1973. In this year, the largest suspended sediment concentration was measured.

The seismic activity in basin produces a huge amount of sediment. The middle of the Vakhsh river basin is a region of very high seismicity. Epicentres of many earthquakes are located there. One of the most catastrophic was the earthquake of 1949, which greatly increased the sediment run-off from glaciated areas of the watershed (Shcheglova 1974).

7.1.2 Maximum sediment delivery period

Shcheglova and Chizhov (1981) discussed about the sediment transport from the glacierized basins in the Central Asia. The washing out of sediments from the glacier zone in this region occurs mainly during the period of intensive melting, i.e. from July to September. Snow and ice on the tongues of large glaciers, such as lednik Fedchenko and lednik Zarafshan, which descent to a low altitude, can begin melting earlier, sometimes in June or even in May, but the washing out of sediments at this time is not high because the area of melting is limited, the air temperature is not high, and sunny weather often changes into snow falls.The first increase of sediment transport in spring depends on rains and on melting of snow at lower altitudes, and is not very large.

7.1.3 Relationships between suspended-sediment concentration and discharge

In order to assess the nature of sediment supply beneath the glacier and the interaction of water flow with sediments at the bed, the relationship between suspended sediment concentration and discharge was investigated. Suspended sediment concentration discharge relationship of the form $S_s = aQ^b$, where S_s is suspended sediment concentration, Q discharge, and a and b best fit estimated parameters, were fitted to data collected in 1974, using r^2 as an index of goodness of fit of the model. The range of best fit parameters and low degrees of fit indicate that the relationship between sediment concentration and discharge in the Gornera is non-stationary, and varies between rising and falling limbs of diurnal hydrographs. Better fit of the model applied to relationships between suspended sediment transport and discharge in glacial melt water streams (Church 1972; Ostrem, 1975) probably results from the use of the statistically spurious association between discharge and sediment transport (Benson, 1965). Use of the master rating curve to estimate suspended sediment concentration for periods when samples are not collected would result in considerable inaccuracy. In non-glacial catchments, gross errors in the assessment of sediment load arise from use of sediment rating curves, especially when hysteresis is present (Walling, 1977).

The effects of hysteresis dynamics in the relationship between sediment concentration and discharge in the Gornera are illustrated by rating loops for 18-19 August 1975, cycling in a clockwise direction and including involutions (Figure 3). Clockwise hysteresis loops result from greater concentrations of suspended sediments on the rising limb of the diurnal hydrograph than at equivalent discharges during the falling stage, resulting from the flushing out of sediment collected at margins and beds of subglacial streams during low flows. A distinct loop occurred each day during periods of sustained ablation, often with figure-of-eight sub-loops and involutions, reflecting irregularity in sediment availability. More regular relationships, in which daily peaks of sediment concentration precede discharge peaks by several hours, have been shown for glacial melt streams in Norway and on Baffin Island (Ostrem et al., 1967; Ostrem, 1975).

In regions where seasonal variation in erosion processes and source areas are controlled by floods generated by both spring snowmelt and summer storms, seasonal variation in sediment yield may mask any relationship with discharge (Walling, 1988). The relationship between sediment and discharge and the character of suspended sediment transport have been investigated for individual hydrological events (Heidel, 1956; Guy, 1964; Arnborg et al., 1967; Carson et al., 1973; Loughran, 1976; Wood, 1977; Marcus, 1989; Williams, 1989). Variations in sediment concentration have been attributed to exhaustion and replenishment of the sediment supply, differences in travel distance between source areas and the locations of the measuring station, the location of sediment source areas and the existence of a time lag between sediment concentration and discharge peaks. Williams (1989) developed models for sediment rating relationships (linear and curved) for individual hydrological events by comparing sediment concentration and discharge ratios at a given discharge on the rising and falling limbs of discharge hydrographs. Although he summarized the physiographical and hydrological reasons for the existence of each type of relationship associated with sediment rating curves, only partial understanding of the controlling factors exists.

7.1.4 Relationship between sediment transport and air temperature

The air temperature over glaciers is the main factor, which controls the sediment washing-out from the glaciated areas. A large or small sediment run-off usually occurs synchronously on nearly all glacial rivers in the western part of Central Asia. In 1950 and in 1973, for example, when the summers were very hot, the sediment transport of glacial rivers was 1.4 to 3.3 times larger than normal. It was especially large on rivers emerging from glaciers located at very high altitudes, e.g., the Lyangar River falling into Ozero Sarezskoye in the Pamir. The solid discharge here is usually low because of weak melting in ordinary summers; sediments accumulating on the glacier for many years can be washed off during a hot summer. In 1973 the sediment run-off

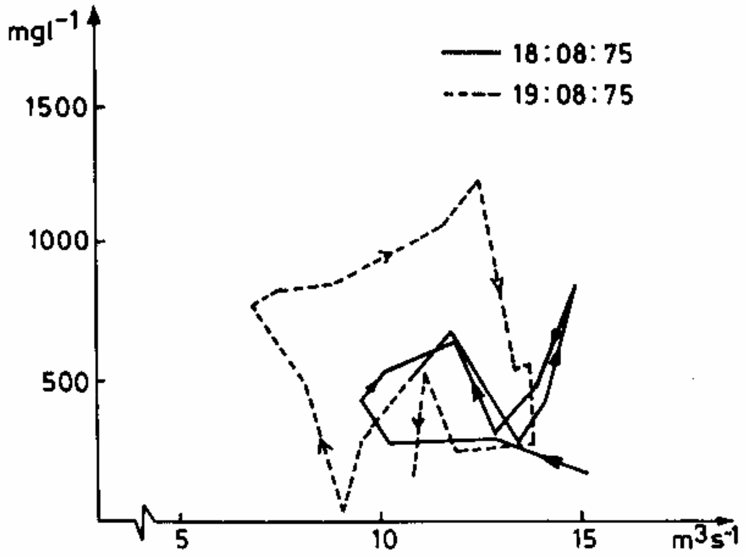

Figure 3 Hysteresis rating loops for suspended-sediment concentration with discharge in the Gornera for 18 & 19 August, 1975. Clockwise loops and involutions occurred on both days. (based on Collins 1979)

of the Lyangar River was 4.2 times greater than normal. Also, the probability of strong glacial mudflows increases in very hot summers.

In years with cool summers, often preceded by heavy winter snow falls, the sediment runoff is usually much smaller than normal. Such was the case in 1969 when some glaciers (in the Pskem river basin, for example), remained under snow for the entire summer (Shchetinnikov 1976). Summer snowfall also decreases sediment runoff. In the Pamir they do not occur very often, but they happen more frequently in the eastern part of Central Asia, i.e. in Central and Easterm Tien Shan. Their influence upon intensity of melting is even greater in those mountain regions of the Soviet Union lying farther towards the east, e.g. Altayskiy Kray (Tronov 1966)

Shcheglova (1981) obtained an exponential relationship plotting a mean sediment discharge R of a glacier river for a certain period versus a mean temperature T for the same period . The relationship is expressed as

$$R = a \exp(bT)$$

where R is the average monthly sediment discharge, T is the average monthly temperature at lednik Fedchenko meteorological station, and a and b are parameters which differ for each river basin. The value of a changes from 0.66 to 256 and for b it varies from 0.36 to 0.66. Their magnitudes are controlled by the areas and the topography of the watersheds and the areas of glaciers. The more glaciated the watershed gives a closer the relationship.

7.2 Multiple correlation concerned with different parameters relevant to sediment discharge

The analysis of factors which control the sediment transport from the glacier zone has shown that, as well as the climatic factors, the glacio-morphometric characteristics of the watersheds should also be considered. The most important of these is the area of the largest galcier in a watershed (Shcheglova and Lebedeva 1978). Such a conclusion has been drawn using the method of multiple correlation (Alekseyev 1971). Relationships between the specific suspended sediment run-off from the glacier zone M and factors which control it were obtained. Data concerning the sediment runoff of many glacial rivers were used, namely from 37 basins with areas varying up to 31,000 km^2 in the Caucasus, Polar Urals, Alps, and Kamchatka, as well as in Central Asia. The climatic characteristic chosen was the mean summer temperature T (July to September) at the lower limit of the glaciers in the watershed. The study shown that the contribution of the temperature amounts to 52%, the remaining 48% is given by the area of the biggest glacier F. The contribution of the area of the small glaciers in the watershed has been statistically proved to be insignificant. The final relation is shown in Figure 4. The coefficient of multiple correlation is 0.752 ± 0.073.

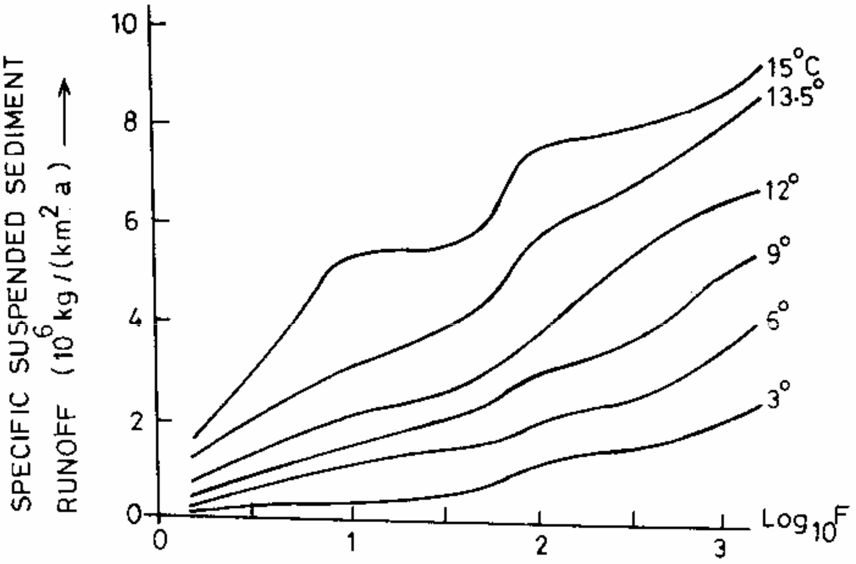

Figure 4 The specific suspended sedment runoff plotted against the area F in km^2 of the largest glacier in the watershed of different levels of the mean summer temperature t (july septemer) at the lower limit of glacier in the watershed. (based on Shcheglova and Chizhov 1981)

When the mean summer temperature at the lower limit of glaciers is not high, the washing out of sediments is small and nearly independent of the area of the biggest glacier in the watershed. Such conditions are typical for high altitude glaciers of the central Tien Shan. But when the temperature there is high (as is the case for such glaciers as lednik Fedchenko and Lednik Zaravshankiy), the influence of the morphological factor greatly increases. The specific quantity of suspended sediment washed out from the glacier zone M for watersheds having large glaciers reaches 8×10^6 kg $km^{-2}yr^{-1}$ as shown by Figure 4. Observations show that the magnitude of M for some watersheds can be even greater than this, e.g. for the Vakhsh river basin, $M = 14.9 \times 10^6$ kg $km^{-2}yr^{-1}$. This deflection from the relationship is due to the seismic activity of the region. The quantity of sediments added to the usual value because of seismicity can, however, be eliminated (Shcheglova 1974). Then $M = 8.81 \times 10^6$ kg $km^{-2}yr^{-1}$, which is close to the relationship of Figure 4.

It seems evident that the geological structure of a watershed is of little significance for the value of sediment run-off because the glacier river basins used for the relationship of Figure 4 are of quite different geological character.

7.3 Suspended sediment storage within the study basin

The data from the glacier de Tsidjiore Nouve, Switzerland, found that 50% of the sediment transported by the glacier is deposited in the lateral moraines and in the portal regions (Small, 1987). Most of the load of the Hunza River, Karakoram, is picked up from valley floor even if it is of glacial origin and transported by glacial meltwater (Ferguson, 1984). Similar results were obtained by the study of Hasnain and Chauhan (1993) on the Alaknanda basin, Garhwal Himalaya, that sediment load near the glacier portal was 3.7×10^6 t day^{-1}, and it decreased to 1.12×10^6 t day^{-1} at Devprayag. Thus almost 70% of the suspended sediment load obtained from the glacier at the source goes into temporary storage in the alpine watershed and subsequently is removed in periods of high discharge during the monsoonal months. Streams fed by glacier meltwaters along the Alaknanda River showed high sediment load as compared with those fed by non glacier sources such as springs and ground water.

8.0 COMPARISON OF SEDIMENTATION FROM ARCTIC GLACIERS WITH TEMPERATE GLACIERS

Limited studies are carried out to understand the suspended sediment transfer processes in High-Arctic environments, such as Svalbard (Hodson et al. 1998), as compared to the studies in the temperate glacier basins (Bogen, 1989; Gurnell et al.,1996). Detailed systematic study including the effect of thermal regimes, mass balance changes and surging on fluvial suspended sediment transfer are very much fragmentary (Kostrzewski et al., 1989). Even the few studies carried out to estimate the suspended sediment yields in Svalbard suggest that in the High Arctic region suspended sediment becomes increasingly available to the fluvial system through the ablation season. For example, Repp (1988), Bogen (1991), Vatne et al. (1992) and Hodgkins (1996) reported that the sediment concentrations and sediment availability to river systems may increase through the ablation season in the High Arctic region. These results are in contrast to the behaviour of Alpine and temperate glacier basin studies. In the temperate glacier basins the seasonal maximum in suspended sediment concentration in relation to discharge usually occurs at an earlier stage of the ablation season (Gurnell, 1987; Gurnell et al., 1994). It has been suggested that such trend in Alpine glacier basins is associated with the establishment and evolution of a subglacial drainage system. As ablation season progresses, the distributed drainage system of the alpine glacier is gradually replaced by a relatively stable conduit system (Tranter et al., 1996). Under such conditions, a gradual exhaustion of fine sediments that are available to the subglacial drainage network takes place (Gurnell, 1987). In Alpine glacier basins, the glacier bed has been suggested to be the dominant suspended sediment source area (Gurnell et al., 1996), although inputs of suspended sediment from the proglacial valley train have also been recognized (Gurnell, 1987; Richards, 1984).

Suspended sediment yields in the Svalbard glacier basin (86 to 110 t km^{-2} yr^{-1}) in the high Arctic region are found lower than many estimates from either temperate glaciers at lower latitudes (Bogen, 1991; Gurnell et al., 1996). The relatively low suspended sediment yields compared with those representative for many Alpine glacier basins and the apparent increase in the availability of suspended sediment to rising discharge throughout the ablation season are most likely to result from the absence of sub-glacial sediment delivery processes. The dominance of cold ice over ice at the pressure melting point throughout Austre Broggerbreen does not permit meltwaters to access the glacier bed. Thus, the predominance of cold-based ice renders subglacial drainage of water negligible (Hodson, 1994) and subglacial sediment sources are unlikely significant at or within any predominantly cold-based glacier basin. Meltwater runoff therefore follows supraglacial, englacial and marginal pathways. Fine sediments for transport by the meltwater stream are supplied by slope processes, and by overland flow generated by rainfall and snowmelt from both ice marginal and proglacial sources.

An alternative explanation for increased sediment availability within the glacial part of the catchment in the High Arctic region can be based upon suspended sediment supplied from lateral and marginal moraines and slope sediment sources. The presence of extensive lateral moraines and slopes exposed during recent glacial retreat, coupled with the tendency for the drainage system to follow ice marginal pathways, allowed increasing contact between sources of fine material and melt water as the ablation season progressed. Solifluction and slope failure produce extensive sediment source areas. In addition, sediment rich runoff was observed to drain from the moraines to the river. The slope and moraine sources provided increasing amounts of fine sediment as the recession of the snowpack initiated mass movement over a progressively larger area. Increased suspended sediment availability may also include delivery of sediment from the proglacial sandur. The increase in active layer depth caused by ground thaw would allow sediment to be tapped more readily from both the proglacial and ice marginal sediment sources as the ablation season progresses. Thus ground thaw and snowpack recession were probably jointly responsible for effectively increasing the suspended sediment contributing area. Once mobilized, the most likely depositional sites for the sediment are either the low gradient sandur or the fiord. Thus, whilst the glacierized area can be seen predominantly as a sediment source, the sandur can act as both a source and a sink for fluvial suspended sediment. The net effect of these sources and sinks is likely to vary through the season.

Hodson et al. (1998) found that use of suspended sediment rating curves (the estimated relationships between suspended sediment concentration and discharge) for suspended sediment concentration, provide scatter and hysteresis very frequently. However, the nature of the hysteresis at different time scales and the amount and timing of extreme values may be combined with the strength of the association between the two variables to provide useful information upon which process inferences can be drawn. Clockwise, diurnal hysteresis between the two variables results from this phasing difference and also from the exhaustion of fine sediments over the diurnal discharge cycle.

9.0 VARIATION IN GRAIN SIZE DISTRIBUTION IN GLACIER MELT STREAMS

The mineralogical compositions, accessibility for weathering, erosion, and transport play the most important role in the grain size distribution of the suspended sediment. The analysis of the composition of suspended sediment in the proglacial streams becomes very important because this water is used in hydropower generation (Ziegler, 1974). The efficiency of these hydropower schemes is affected by the type and size of suspended particles. Walling and Moorehead (1987) argued that the grain size of suspended sediments has also an impact on the trap efficiency of reservoirs. Additionally, the study of grain size distributions can provide important information on the interactions between melt water and geological composition such as composition of till at the glacier bed, lateral and medial moraine on the glacier. In the study of glaciofluvial sediment transport, most works have dealt with relationships between discharge and load or concentration of suspended sediment transport (Ostrem 1975; Collins, 1979b; Gurnell, 1982). Less consideration has been given to grain size distributions of sediments transported or settled in glacial melt water streams (Rainwater and Guy, 1961; Ziegler, 1974; Bogen, 1979, 1980; Fenna and Gomez, 1989; Karlsen, 1991). Karlsen (1991) studied the temporal variations in grain-size distribution of suspended sediment in a glacial melt water stream and compared the variations with discharge and sediment concentration.

Bagnold and Barndorff-Nielsen (1980) and Christiansen et al. (1984) showed that sediments transported by water are better described by using hyperbolic distributions. Grain size distributions of suspended sediments in glacial melt water streams can be described as hyperbolic rather than log-normal. High sediment concentration does not necessarily reflect a high concentration of coarse grains. Additionally, concentration of coarse grains is independent of discharge. There is no direct correlation between discharge and distribution parameters, and no single parameter definitely represents the grain size distributions better than any other parameters. However, based on the results of Rainwater and Guy (1961) and Bogen (1980) there is the possibility that the influence of discharge will stand out more clearly at a sampling site farther down stream, as the importance of the glacier bed conditions diminishes.

Rainwater and Guy (1961) suggested that hydraulics probably influences the grain size distributions more with increasing distance from the glacier, as the importance of sub-glacial sediment sources declines. Conditions other than hydraulic ones are responsible for the grain size distribution of the suspended sediment. This is in agreement with the result of Bogen (1979) who studied grain size distributions of suspended sediment in several Norwegian proglacial and non-glacial streams. Bogen (1980) found that temporary deposition and erosion of sediments at channel bed during falling and rising stages of water caused short time variations in grain size distributions. He concluded that this, together with flow competence, was the determinant condition.

10.0 SEDIMENTATION STUDIES CARRIED OUT IN THE HIMALAYAS

The Himalayas are the source of many perennial rivers that offer immense hydropower potential. Many projects have already been completed and many are under construction. These projects are of considerable national and local importance in terms of hydropower generation and subsequent socio-economic development of the region. The success of these projects depends to a great extent upon regular and sediment free water flow. Some studies have been carried out for the suspended sediment load estimation in the Himalayan region and these studies suggest a high rate of sediment load in the Himalayan rivers which is a threat to existing or planned hydroelectric power projects by shortening their life. It has been reported that 28-77 % of the catchment areas of the Himalayan rivers are in need of priority treatment for sediment control if efficient hydroelectricity projects are to be completed (Das et al., 1981); yet the percentage increase in rate of sediment inflow varies from 39.9 to 449.9% (Gupta, 1980; Das et al., 1981; Mukherjee et al., 1985; Tejwani, 1987). These studies, however, dealt with very large catchment areas and do not provide a precise assessment of the problem in terms of the High Himalayan basins.

10.1 Satluj basin

Sharma et al. (1991) have studied suspended sediment load in the Satluj river basin in detail and identified the sediment load at different sites within the basin. About 80% of the annual flow of the Satluj River system from basins in the High Himalaya, that is, Tibet, Spiti and Kinnaur, occurs between May and September and is primarily due to snow melt. Suspended sediment increases exponentially with increase in discharge and occurs in very high concentrations during June, July, and August. The Spiti River experiences a higher volume of water but less sediment relative to the other two basins. The high suspended sediment concentrations in the river system during the summer months and reduced water supply during winter will lower the operational efficiency of hydroelectric projects being planned for the Satluj River. Annual sediment in the Bhakra Reservoir is of the order of 35.8×10^6 m^3, giving an average 50 cm thick sediment layer (Anonymous, 1986). At this rate the effective life of the Bhakra reservoir for power generation is calculated to be only about 150 years and the reservoir will be fully silted up in about 400 years. Dredging operations in reservoirs are invariably difficult and expensive. There is considerable evidence, however, that these high rates of sedimentation can be reduced by the application of corrective treatment measures in the upper catchments (Gupta, 1980; Das et al. 1981; Jiang et al., 1981; Narayana, 1987). Before such measures can be seriously contemplated an assessment of the magnitude of sedimentation in different river basins and the determination of the point sources will be required.

10.1.1 Suspended sediment concentration

The suspended sediment concentration begins to increase as the discharge increases from April onward. It remains low during April and May and increases dramatically at the beginning of June. It remains at quite high levels until the third week of August when it begins to fall again. By the end of September the concentration is very low and between October and March it is negligible. Sharma et al. (1991) reported that Satluj and Spiti concentrations at Khab during the same year and period varied between 2,000 and 4000 and between 1000 and 2000 mgl^{-1}, respectively . The concentration levels for a particular year, however, cannot be taken as a general rule as there is considerable annual variation and variation between the same months of different years. The mean monthly concentrations at Wangtu for April, May, June, July, August, and September were 234, 496, 2611, 2819, 2612, and 664 mgl^{-1}, respectively, with CV's from 45 to 58%. The monthly concentrations for the Sutlej and the Spiti at Khab from April to September were even more variable than for the Satluj at Wangtu, having CV's from 58 to 169%. However, the concentrations were relatively higher for the Satluj and lower for the Spiti at Khab, compared to the Satluj at Wangtu. The sudden increase of the sediment concentrations in the river system may occur more or less simultaneously. For instance, concentrations varying from 12,000 to 14,000 mgl^{-1} shot up on 10 August 1982 simultaneously for each of the sub-catchments. Suspended sediment concentration increased exponentially with increase in discharge (Sharma et al., 1991). Although the relationship shows interannual variation, it is quite precise for certain years. A similar type of relationship between discharge and suspended sediment with interannual variation has been reported by Dunne (1977).

10.1.2 Suspended sediment load

The mean annual suspended sediment load in the Satluj at Wangtu has been estimated to be approximately 18.7×10^6 m^3, or 26.2×10^6 tonnes. The loads calculated for the Spiti and for the Satluj at Khab were 5.6×10^6 m^3 and 5.0×10^6 m^3, respectively. The residual value for Kinnaur, therefore, would be 8.1×10^6 m^3. The annual sediment loads were more variable than the discharges with CV's of 46.4, 67.1, and 50.7% for the Satluj at Wangtu, for the Spiti at Khab, and for the Satluj at Khab, respectively.

Although the area of the Kinnaur catchment and its relative water yield is less than that of the Spiti, its sediment yields are almost 1.5 times that of the latter. Accordingly, the annual sedimentation rate from the Kinnaur catchment is 1571 $m^3/km^2/yr$ compared to 953 $m^3/ km^2/yr$ from the Spiti catchment (Sharma et al., 1991). Sedimentation rate from Tibet is relatively low: only 137 $m^3/ km^2/yr$. The Tehri catchment of 7511 km^2 (of which 2328 km^2 are snow clad in the Himalaya) contributes 14.6×10^6 tonnes of silt annually (Singha and Gupta, 1982); it also gives a sedimentation rate of 1390 m^3/ km^2/yr, similar to that of the Kinnaur catchment. The actual sedimentation rates of the Kinnaur and Spiti catchments are much higher than the assumed figure (360 m^3/ km^2/yr) on which the earlier designs of reservoirs in India are based (Varsheney, 1979). Of the annual sediment of 35.8 × 10^6 m^3 deposited in the Bhakra reservoir (Anonymous, 1986), half (52.2 percent) is being added from the Tibetan, Spiti, and Kinnaur catchments, their individual contributions being 14.0, 15.6 and 22.6%, respectively. Thus, higher than calculated sedimentation from the Kinnaur and Spiti catchments will hamper the operational efficiency of hydroelectric projects to be built on the Satluj River system in Kinnaur and Spiti and this will also lead to a shortening of the original expected life of the projects. Table 4 shows annual suspended sediment load and its composition observed at different locations in the Satluj river. A comparision of sediment yield observed for different Himalayan catchments is given in Table 5.

Table 4: Composition of suspended sediment in the Satluj river system (1977-1985) (Sharma et al., 1991)

River/Site	Annual Suspended sediment load ($10^6 m^3$)	Annual Suspended sediment load (10^6 tonnes)	Fine (%) (<0.075mm)	Medium (%) (0.075-0.20mm)	Coarse (%) (>0.20 mm)
Sutlaj at Khab	5.0	7.0	64.1	22.3	13.6
Spiti at Khab	5.6	7.84	66.4	21.1	12.4
Sutlaj at Wangtu	18.7	26.2	59.9	23.2	16.9

Table 5: A comparison of sediment yield observed for different Himalayan catchments

Catchment	Sediment Yield ($m^3/km^2/yr$)	Sediment yield ($t/km^2/yr$)
Kinnaur	1571	2199.4
Spiti	953	1334.2
Tibet	137	191.8
Tehri	1390	1946.0

10.2 Chenab Basin

The sediment yield response of snow and glacier dominated catchments in the Himalayas is different from rainfed catchments in the rest of India. Rao et al. (1997) attempted to relate sediment yield with geomorphological, landuse and climatic parameters for the Chenab (22,200 km^2) basin, which is a large Himalayan basin. Sediment yield characteristics in the Chenab basin vary depending on the season. During the winter season (October-March) the sediment yield is minimal and is less than 5-10% of the annual yield. During premonsoon season (April-June) the seasonal snow cover melts in the intermediate and upper reaches and lower reaches receive rain. Thus, a significant sediment yield is observed from the catchment in the premonsoon season. During the monsoon season (July-Sept.) rainfall contribution to flows is very high in the lower reaches and gradually tapers at elevations of about 4,000 m (Singh et al., 1995). Air temperatures are also at their highest during the season resulting in snow and glacier melt from permanent snow covered zones. Consequently a major part of the sediment yield is received during the monsoon season. Average sediment yields for annual and monsoon season periods in terms of coarse, medium and fine sediment are shown in Table 6.

Table 6: Average sediment yields in the Chenab basin at different locations along with their composition during the monsoon period (Rao et al., 1997).

Site	Annual average Sediment yield (t/km^2/yr)	Monsoon Season			Total Sediment yield For monsoon Period (Jul.- Sep.) (t/km^2/yr)
		Fine	Medium	Coarse	
Akhnoor	1029	455.9	180.8	85.9	722.7
Benzwar	1597	694.5	360.9	169.6	1225.0
Dhamkund	1900	533.5	386.4	314.3	1234.3
Ghousal	513	221.2	90.3	69.7	381.3
Kuriya	878	300.9	152.4	138.9	592.3
Premnagar	1363	222.9	112.9	102.9	438.7
Sirshi	939	221.4	186.6	146.7	554.8
Tandi	371	164.0	70.6	51.3	286.0
Tillar	373	92.4	62.2	40.7	195.4

The rates of suspended sediment transport in the Chenab river are high as compared with other river systems in India (with exception of Ganges) (Sundd ,1991) and in the world (Holeman, 1968; Milliman and Medade, 1983).

The precipitation and runoff characteristics in the Chenab basin influence sediment yield to a large extent. Snowmelt and glacier melt runoff contribution increases with elevation, while rainfall decreases with elevation in the upper reaches (Rao et al., 1996; Singh and Jain, 1993). To verify, how far rain is responsible for sediment production in various subbasins of Chenab located at different elevations, mean weighted rainfall during the monsoon (Jul. – Sep.) in each sub-basin was correlated (log-linearly) with sediment yield per unit area using 10 years of concurrent data, assuming that catchment characteristics remained unchanged during the period. The correlation coefficients, r, shown in Table 7, with exception of Kuriya indicate less sediment yield on rainfall in the upper reaches as compared with the lower reaches of Chenab basin. In other words rainfall may have little to do with the sediment yield in the upper reaches of Chenab catchment. The amounts of mean rainfall during the monsoon season (July-Sep.) and the winter season (Oct.-Mar.) decreases with increase in elevation (Table 7). Consequently sediment response characteristics vary markedly between the upper and lower reaches of the catchment and hence the low coefficient of correlation for Kuriya station in the transition zone. The transition zones also experience rain-on-snow phenomena. Some of the reasons besides rainfall may be attributed to the prevailing geologic and soil conditions and melt runoff from permanent snow cover zones with glaciers in the upper reaches, as compared with the lower reaches.

Table 7: Correlation of mean basin monsoon rainfall with sediment yield (t/km^2) (Rao et al., 1997)

Sediment Station	Basin average winter rainfall up to respective gauging sites (mm)	Elevation of sediment gauging station (m)	Basin average monsoon rainfall up to respective gauging sites (mm)	Correlation coefficient Between mean weighted rainfall and sediment yield (r)
Akhnoor	588	305	740	0.61
Dhamkund	277	600	353	0.70
Premnagar	201	886	252	0.75
Kuriya	226	1,106	229	0.16
Benzwar	408	1,135	197	0.66
Sirshi	103	1,162	170	0.50
Tillar	71	2,066	153	0.50
Tandi	15	2,846	90	0.33
Ghousal	17	2,850	90	0.44

10.3 Himalayan glaciated region

Alpine glacial catchments exhibit high rates of chemical weathering (Reynolds and Johnson, 1972). Portal or snout melt waters which drain from beneath the glaciers consist of two components (Collins, 1979b). One component is concentrated, the subglacial component and represents water which flows at or near the base of the glacier, in contact with basal debris. The residence time of the subglacial component in the hydrological system is relatively long, which promotes chemical weathering and solute acquisition. The second is the dilute englacial component and represents waters produced by diurnal melting cycles on the glacier surface. Water flow through the englacial hydrologic system. Predominantly through the ice walled conduits have short residence time (Rothilsberger 1972). Subglacial and englacial water mixes and emerges from the glacier portal as torrent.

As such limited investigations are carried out for suspended sediment concentration and load in the high altitude region of Himalayas which consists of a large part covered by the glaciers. Monthly discharge, rain and sediment reported by Hasnian and Thayyen (1999) for one ablation period (1994) for the Dokriani glacier located in the Garhwal Himalayas is given in Table 8. The concentration of suspended sediment in glacier melt waters is found highly variable (Hasnian and Thayyen, 1999; Singh and Ramasastri, 1999). It has been suggested that this variability results from changes in sediment supply from the subglacial channel system (Ostrem, 1975), which may reflect the seasonal development of the subglacial drainage system (Collins, 1979b).

Table 8: Monthly discharge, sediment flux, and rainfall during the 1994 ablation period (Hasnian and Thayyen, 1999)

Month	Total Discharge ($10^4 m^3$)	Discharge (%)	Sediment Flux (10^4 tonnes)	Sediment Flux (%)	Rainfall (mm)	Rainfall (%)
May	196	3	0.043	0.28	3.8	-
June	868	14	4	26	115	9
July	2188	35	8	52	500	39
August	1785	29	3	18	435	34
September	910	15	0.52	3	189	15
October	292	5	0.02	0.18	26	2
Total	6238		15		1269	

Hasnian and Thayyen (1999) reported that in the month of June, a rise of the transient snowline is associated with a fourfold increase in discharge volume and a total suspended sediment transport of 4 × 10^4 tonnes (Table 8). This may result from new areas of the glacier bed that were hydraulically isolated during May becoming integrated with the main sub-glacial drainage system and releasing large quantities of sediment from basal storage during June. Despite higher discharges in early July, daily sediment loads fail to rise to the loads observed in June, suggesting that there is some exhaustion in sediment supply. Nevertheless, the high flows in July, transport the highest monthly total sediment load of 8 × 10^4 tonnes (Table 8). During August, September and October there is a recession in both discharge and sediment transport; one exception to this trend is a major discharge and sediment transport event in late August which is associated with a severe storm and flash flood.

The temporal characteristics of suspended sediment transfer include the arrival of the suspended sediment concentration maximum in advance of the discharge maximum. The lag between the suspended sediment concentration and discharge time series also changes during the ablation season, which may be possible due to changes in the amount of suspended sediment available to the fluvial system are associated with adjustments in the dominance of different suspended sediment source areas. Discharge as well as suspended sediment concentration peaks occur progressively earlier in the day, resulting in shorter rising limbs and extended falling limbs of both the diurnal hydrograph and sediment concentration graph. These characteristics probably result in changes in the structure at the glacial drainage system through the ablation season (Bogen, 1996). Table 9 compares the observations reported in this paper with discharge and sediment transport data from other Himalayan glaciers. Regional climatic conditions are clearly important in influencing energy availability for melting, the length of monsoon season and the quantity of precipitation and these in turn influence the timing and amount of sediment delivery from the glacier basin.

Table 9: Annual sediment transport data for three important Himalayan glaciers

Glacier	Area $(10^3 km^2)$	Mean annual discharge (km^3)	Glacier -isation (%)	Mean annual sediment transport $(km^2 yr^{-1})$	Source
Batura, Karakoram Pakistan,	0.65	0.93	60	6086.0	Lanzhou Institute(1980)
Langtang, Nepal	0.33	0.45	38	2453.0	Fukushima et al. (1987), Ohta et al.(1987)
Dokriani,Garhwal Himalaya India	0.0096	0.06	60	15751.0	Hasnian and Thayyen,(1999)

Under some events, flow discharge increased by a factor of one and a quarter, but at the same time the suspended sediment transport increased nine times in the same period and then returned to its original value. It should be noticed that the peak in sediment transport occurs earlier than the water discharge peak. This indicates that sediment transport reacts quickly to discharge.

11.0 SUSPENDED SEDIMENT FROM DOKRIANI GLACIER

11.1 Study area and its hydrometeorological characteristics

The Garhwal Himalaya lies between latitudes 29° 45'- 31° 30'N and longitudes 78° 02'-80° 07' E encompassing an area of 30,000 km^2. This region contains more than 1020 large and small glaciers covering several hundred square kilometre area by the glaciers (Vohra, 1981). The present study was carried out for the Dokriani glacier (31°49'-31°52' N, 78°47'-78°51' E) located in the Upper Ganga catchment in the Garhwal Himalayas. This glacier originates in the vicinity of Janoli (6633m) and Draupadi ka Danda (5716m) peaks. The melt stream originating from Dokriani glacier is known as Din Gad. This melt stream follows a narrow valley and meets Bhagirathi river near Bhukki village. The Bhagirathi river is also a proglacial river and rises from Gangotri glacier situated about 80 km upstream to the confluence of Din Gad and Bhagirathi river.

Total drainage area of the Dokriani glacier is about 16.13 km^2, out of which about 9.66 km^2 (60%) is covered by snow and ice. The elevation of glacier varies from about 3950-5800 m. The length of this glacier is about 5.5 km whereas its width varies from 0.1-2.0 km from snout to accumulation zone. The altitudinal distribution of glacier area shows that the major part of the glacier is concentrated above 5000m in the basin. In the lower part of the basin, glacier free area is higher than the glaciated area, but upper part of the basin is almost fully occupied by the glacier. The snout of glacier is situated at an elevation of about 4000 m and covered by huge boulders and debris. The ablation part of this glacier is almost covered by debris. The material of these moraines has been derived from the side of valley mainly by frosting. This glacier is bounded by two large lateral moraines, which are about 200-250 m in height. Besides these two lateral moraines, there are several other lateral moraines observed at different altitude. These different levels of moraines indicate the past extension of the glacier. The middle part of the glacier is highly fractured and consists of crevasses, moulins, glacier table and ground moraines. The crevasses are found to be mainly of transverse type, which are wide and long. Sometimes longitudinal crevasses were also seen along the sides of the glacier. A view of the Dokriani glacier is shown in Figure 5. Figure 6 shows the presence of debris available in the ablation zone of glacier, which are also a source of sediment in the glacier melt stream. Stern et al. (1989) reported that the bed rock geology in the Bhagirathi valley consists of mainly of granite and augengneiss. Geology of the glacierised region of Bhagirathi valley consists of mainly of crystallines with occurrences of carbonates and pyritous shales and phyllites (Sarin et al. 1992).

The Himalayan proglacial streams carry about 70 to 85% of their annual flow during the summer monsoon months (Bruijnzeel and Bremmer, 1989). The average rainfall in the Garhwal Himalaya is between 1000 to 2500 mm, of which 50 to 80% falls during the monsoon period

Figure 5: A view of Dokriani Glacier

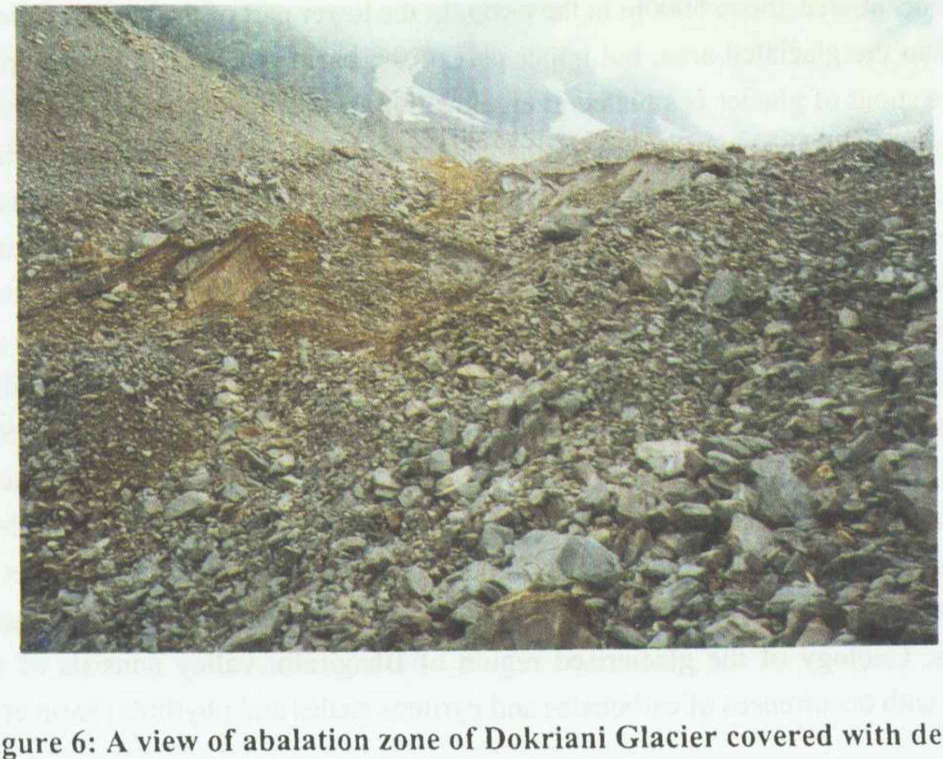

Figure 6: A view of abalation zone of Dokriani Glacier covered with debris

between July and September. Zheng Benxing (1989) has reported the occurrence of Indian monsoon rain near 6000 m. Occasional cloudbursts over the ablation region of the Garhwal Himalaya, cause debris avalanches and debris flows to lower elevations.

11.2 Source of suspended sediment into Dokriani Glacier melt stream

The main sources of sediment production in the glacier fed channel are glacier system, bedrock system and the channel system. The glacier system includes sedimentation from different parts of the glacier such as the accumulation zone, ablation zones, snout and the lateral moraines. The major source of debris deposited over these zones is from the valley walls and from the reworking of the old moraines. From the features of the surface texture of the lateral moraines, it could be expected that chemical and mechanical processes might also produce the lateral moraines sediment into the glacier melt stream (Singh et al.,1995). However, it might not be solely responsible for the production of moraines and suspended sediment. Processes like sliding of rocks and debris, snow and glacier avalanches would dominate to produce moraines and sediment. The glacier and bedrock systems include the abrasion and fracturing of debris and rocks. The abrasion can be described as a process by which bedrock is abraded by the debris present in the basal layer of a glacier i.e. the scouring of rock by rock. Over wide areas in the glaciated regions the bedrock is markedly abraded and is an important element in glacial erosion. The other possible source of sediment is the fracture of rocks beneath the glacier and release of sediment. In the mountain glaciers landslides and rockslides from the surrounding valley walls to the glacier surface are considered a major source of sediment.

Sediment transported by the glacier follows three basic routes: supraglacial, englacial and subglacial. In the glacierized basins, variations in suspended sediment concentration are attributed to the location of sediment source, development of drainage work, exhaustion and replenishment of sediment supply, differences in travel distance between source areas and the location of measuring station. As ablation season progresses the concentration of sediment first increases due to availability of sediment within the subglacial and then reduces due to evacuation of the sediment from the drainage system. The ablation part of almost all the Himalayan glaciers including Dokriani glacier is characterised by an almost continuous surfacial cover of morainic debris. A part of this debris covering the surface of the glacier is also transported down through extensive longitudinal and transverse crevasses into englacial and subglacial tunnels, which becomes the continuous source of sediment into melt stream.

The problems associated with higher rate of suspended sediment, their constitution and structure are of immediate concern in the Garhwal region. To highlight the problem of suspended sediment, one example of Tiloth Power Station at Uttarkashi is cited here. This power station has a capacity of 3 × 30 MW and was commissioned in 1984. A diversion dam is constructed at Maneri Bhali on the Bhagirathi river to divert water to the power station through 8 km long tunnel. There is a peculiar problem of runners damage due to quartz sediment particles. At present only sediment particles having size <0.30 mm and concentration not more than 1,200 ppm are allowed to operate the hydro-power scheme. In the monsoon period concentration increases substantially and sometimes reaches about 10,000 ppm. Therefore, every year during monsoon season power plant is shut down until concentration lowers down to the permissible value of 1,200 ppm. The runners are repaired/replaced every year and sufficient spares parts are kept in store so that runners may be replaced at any time, if required. A major expenditure is incurred in maintaining this power plant.

11.3 Collection and analysis of suspended sediment data

In order to determine the concentration and load of suspended sediment in the Dokriani glacier melt stream, every day two/three samples were collected. At the time of sampling, streamflow was also measured. A known volume of water (500 ml) was scooped from the stream and filtered using Whatman-40 ashless filter paper at the site. The filtered samples were properly packed in polyethylene bags marked with details of samples such as date and time of the sample collection etc. The samples were analyzed in the NIH Water Quality Laboratory at Roorkee. First empty silica crucibles were brought to their constant weight by heating and cooling system. The samples were placed in those crucibles and placed in the oven for a period of more than 24 hours. The temperature of the oven was maintained to 200°C for this period. The ashless filter paper was burnt completely in the high temperature. The crucibles were again weighed with samples of sediment . The net weight of sediment was determined by subtracting the weight of empty crucible from the total weight. Because the amount of sediment was very little, therefore, a electronic balancing machine was used for weighing purpose. Suspended sediment load in a river is evaluated by multiplying suspended sediment concentration by the respective discharge.
The particle size analysis was made using Malvern Mastersizer E instrument.

12.0 RESULTS AND DISCUSSION

12.1 Suspended sediment concentration and load

A plot of mean daily value of suspended sediment load and streamflow with time is given in Figure 7. Analysis of suspended sediment for concentration and load in the Dokriani glacier melt stream for different years shows a wide range of daily suspended sediment concentration (80-3830 ppm) and load (6 -7916 tonnes). Investigations show that streamflow in the melt stream did not change that significantly as suspended sediment concentration/load. Maximum mean daily concentration of suspended sediment observed in June, July, August and September was 2592, 3349, 3830 and 867 ppm, respectively. Mean monthly values of concentration for the corresponding months were computed to be 452, 933, 965 and 275 ppm, indicating highest mean monthly concentration in the month of August followed July. Mean monthly sediment concentration in the months of July and August was found to be about two times that of June, and about three times that of September concentration. On the seasonal basis mean value of suspended sediment concentration is computed to be 748 ppm. Monthly distribution of suspended sediment concentration observed in different years at the gauging site is given in Figure 8.

Figure 9 shows the distribution of load transported through this glacier melt stream. On average suspended sediment transported in the months of June, July, August, and September was 3607, 18733, 20951 and 1794 tonnes, respectively. During a melt season, average value of total suspended sediment transported was computed to be 45085 tonnes. Similar to concentration, maximum sediment load from this glacierized basin was observed in the months of August, followed by July. Maximum runoff was also observed in these two months. Highest value of daily suspended sediment load (7916 tonnes) in the channel was observed on a rainy day with highest rainfall 58mm. During this period high rain occurred for 6 consecutive days continuously. Both higher amount of rain and higher melt rate are expected to contribute to higher amount of suspended sediment in the months of July and August. (Table 10)

Observations suggest that in the glacierized basins almost all the sediment and flow is transported during the melt period comprising of June to September. Assuming suspended sediment yield during melt season equal to annual yield, the suspended sediment yield for the Dokriani glacier basin was computed to be about 2800 t $km^{-2}yr^{-1}$. The iso-erosion rate map of India shows that mean annual erosion rate in India varies from 350 to 2500 t $km^{-2}yr^{-1}$ (Garde and Kothyari,1987). Thus results of present study show that sediment yield from the Dokriani glacier basin is even higher than the maximum value of the sediment yield reported earlier.

Table 10: Monthly rain, discharge and sediment load observed near the snout of the Dokriani glacier in different years

Period	1995			1996			1997			1998		
	Rain (mm)	Discharge (Cumecs)	Sediment Load (tonnes)	Rain (mm)	Discharge (Cumecs)	Sediment Load (tonnes)	Rain (mm)	Discharge (Cumecs)	Sediment Load (tonnes)	Rain (mm)	Discharge (Cumecs)	Sediment Load (tonnes)
Jun.	174	160.2	4282	217	98.1	7210	184	35.0	1713	181	44.6	1225
Jul.	321	290.7	22297	187	231.6	24402	242	164.0	20157	255	149.2	8076
Aug.	423	277.2	24566	413	255.3	24328	308	198.0	25225	359	150.2	9687
Sep.	--	--	--	--	--	--	146	62.0	1795	257	51.0	--

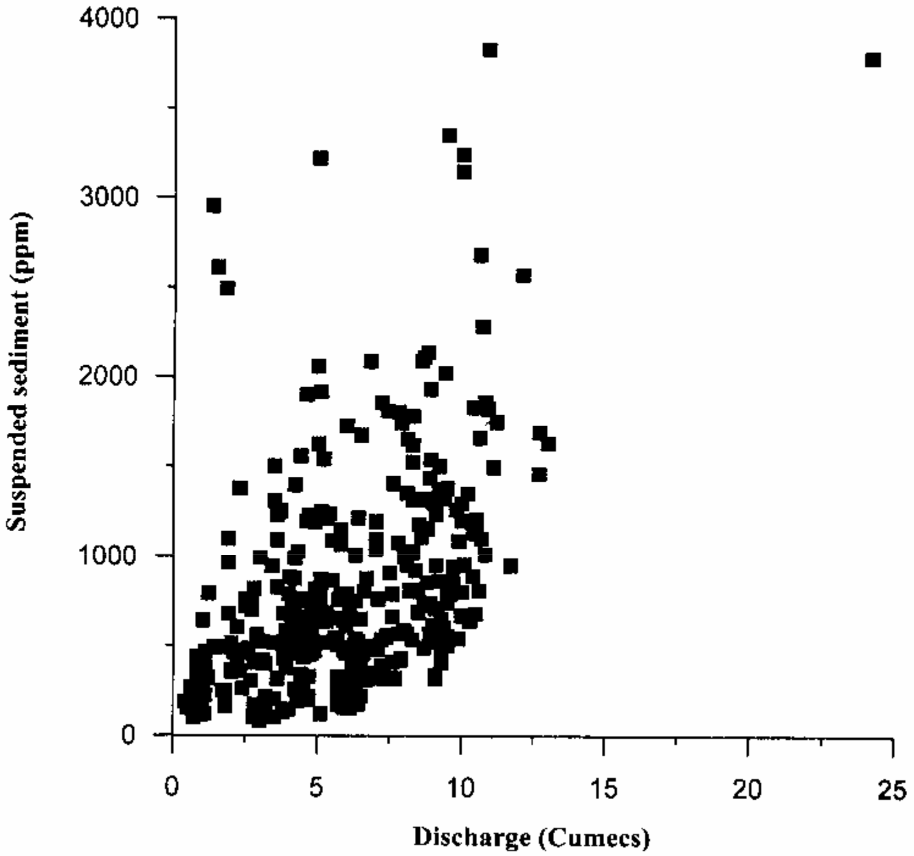

Figure 7: Relationship between discharge and suspended sediment concentration observed at the Dokriani glacier gauging site.

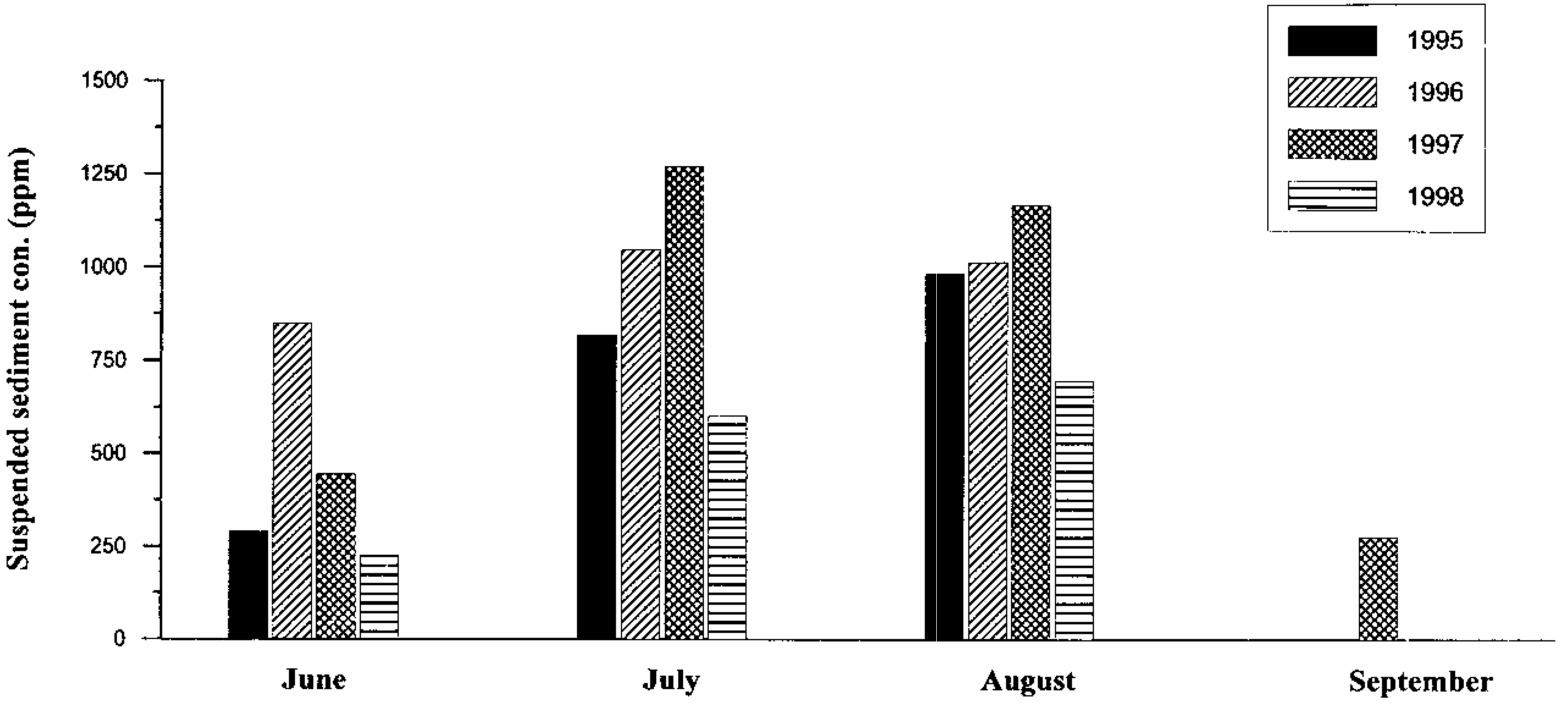

Figure 8: Mean monthly suspended sediment concentration observed at the Dokriani glacier gauging site for different years.

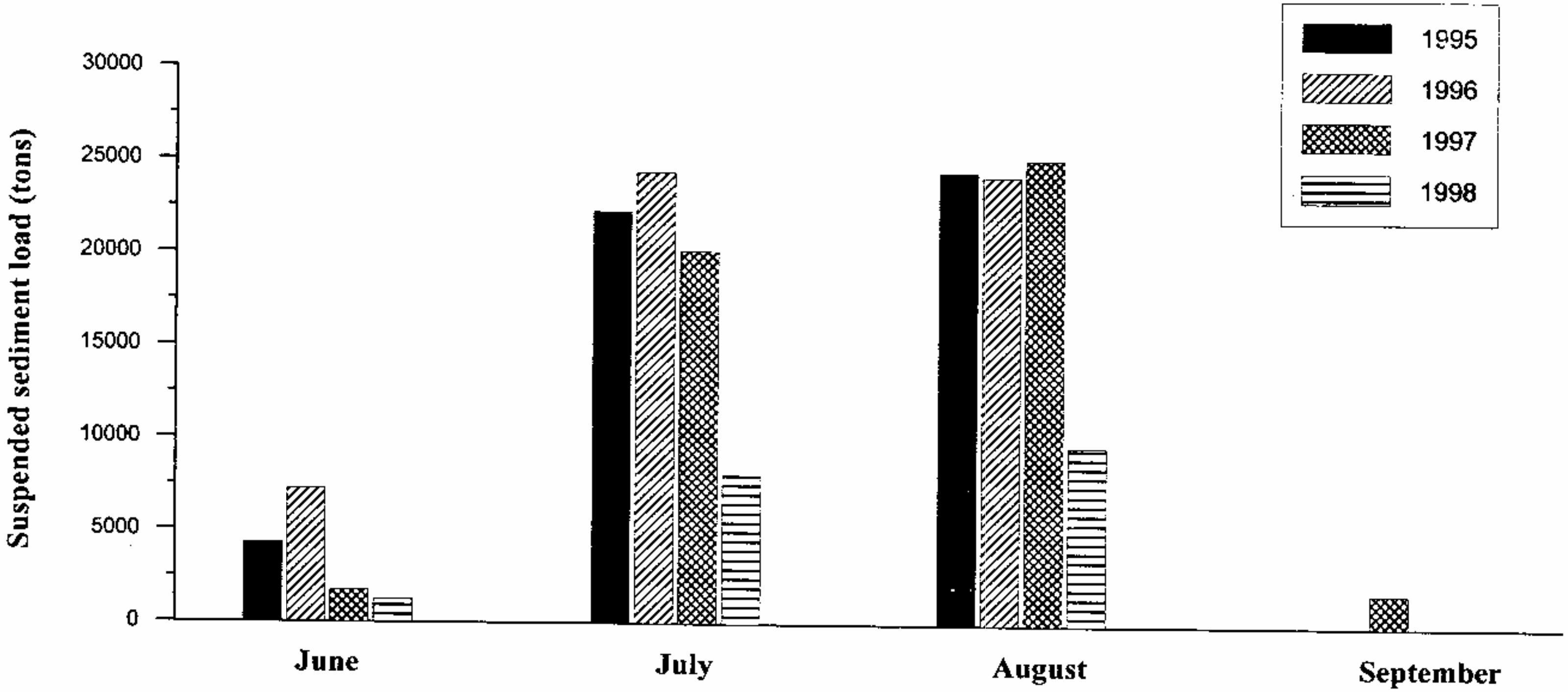

Figure 9: Monthly suspended sediment load observed at the Dokriani glacier gauging site for different years.

12.2 Relationship between discharge and suspended sediment

The relationship between discharge and concentration of suspended sediment on the daily basis was attempted using mean daily discharge and suspended sediment concentration data of 4 years (1995-1998) (Figure10 to Figure 13). It was found that on the daily scale as such no specific relationship was found between either discharge and concentration of suspended sediment or discharge and suspended sediment load. However, broadly suspended sediment concentration or load increased with an increase in discharge. It is understood that sudden increase in sediment concentration in some events without corresponding increase in discharge could be attributed for such poor relationship. Dynamics of the glacier resulting in movement of glacier, slumping of the heavily sediment laden portal ice into the stream, occurrence of good rainfall, landslides and rockslides in the ablation zone and near the snout of glacier are all considered responsible for such variation in the sediment load in the glacier melt stream. The sediment deposited due to landslides and rockslides in the glacier basin is transported to melt stream by rain. Rainfall events contributed very much in eroding sediment from valley side walls and transporting suspended sediment to the channel and the highest value of suspended sediment in the channel was observed on a rainy day. A similar pattern between flow and suspended sediment has been observed in the other glacier melt streams in the Himalayan region (Singh, 1991).

It was understood that occurrence of good rainfall in this region would have distorted the relationship between discharge and suspended sediment concentration/load. In order to investigate the impact of rainfall on the relationship between discharge in the glacier stream and suspended sediment, the data set pertaining to every year was splited into two parts; rainy days data and rain free days data, for all the years and then separate plots between discharge and suspended sediment were prepared. In this analysis, the days with rainfall less than 2.5 mm were considered as rain free days. Results for 1995,1996,1997 and 1998 are shown in Figure 14 to Figure 17. It is found that splitting of data into rainy days and non-rainy days did not improve relationship very much. It further confirms that other processes like landslides, rockslides and movement of glacier etc. are important phenomena for contribution of sediment in the Dokriani glacier melt stream.

Gurnell and Clark (1987) reported the relationship between annual discharge and annual suspended sediment load from the 43 drainage basins covered under four categories, namely, glaciated mountain catchments, basins having glaciated area less than 10%, sub arctic mountain catchments and arctic catchments (Figure18). Broadly Figure 18 indicates higher annual suspended sediment load corresponds to the higher annual discharge. Total mean discharge and suspended sediment load observed from the Dokriani glacier for the whole summer period during four different years, which represent almost the annual values, were also plotted along with the

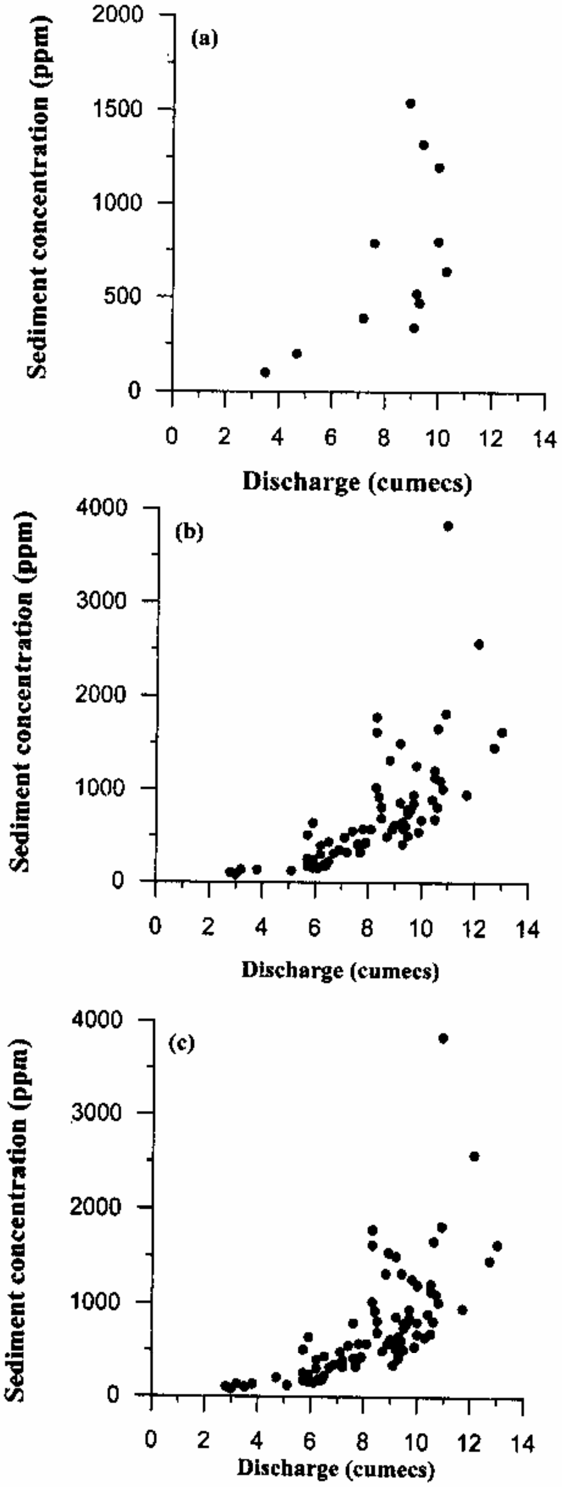

Figure 10 : Relationship between discharge and suspended sediment concentration for summer 1995 data : (a) for non rainy days, (b) for rainy days, (c) for all days.

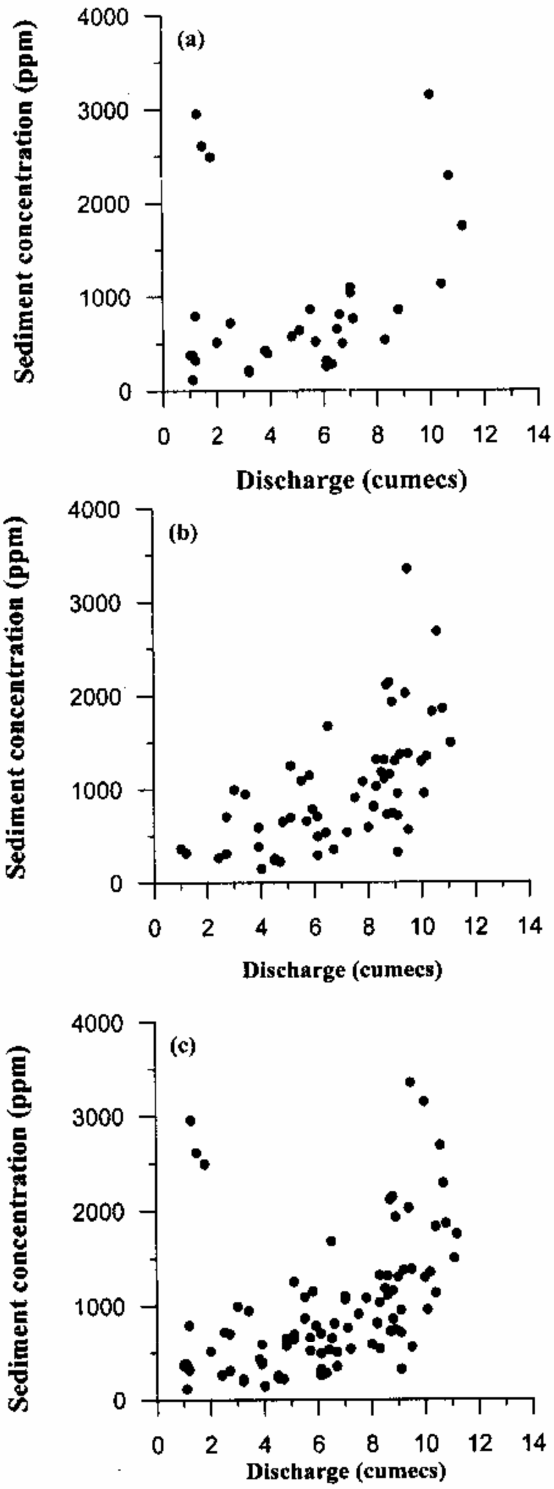

Figure 11 : Relationship between discharge and suspended sediment concentration for summer 1996 data : (a) for non rainy days, (b) for rainy days, (c) for all days.

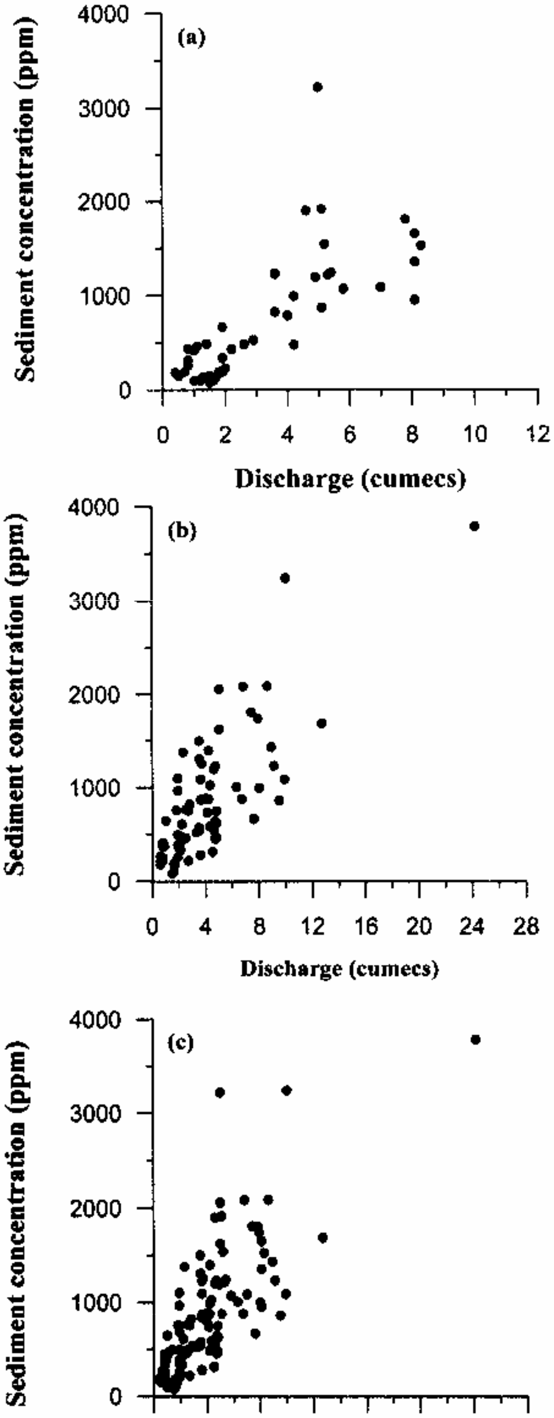

Figure 12 : Relationship between discharge and suspended sediment concentration for summer 1997 data : (a) for non rainy days, (b) for rainy days, (c) for all days.

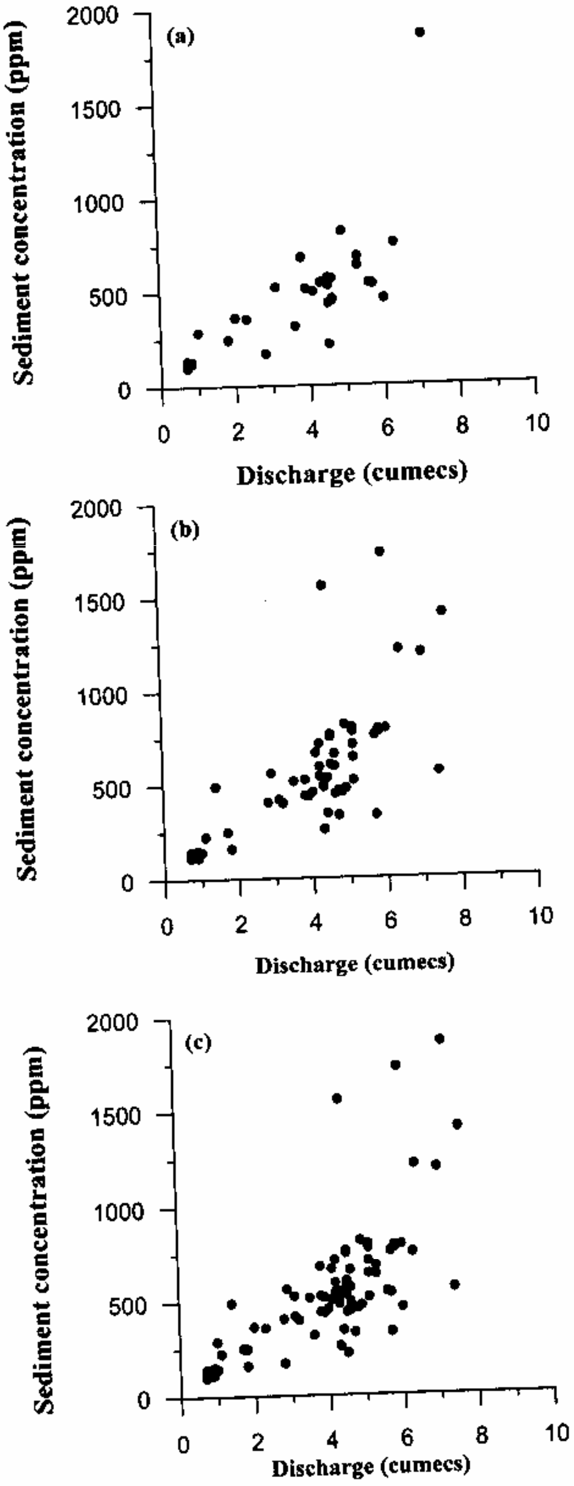

Figure 13 : Relationship between discharge and suspended sediment concentration for summer 1998 data : (a) for non rainy days, (b) for rainy days, (c) for all days.

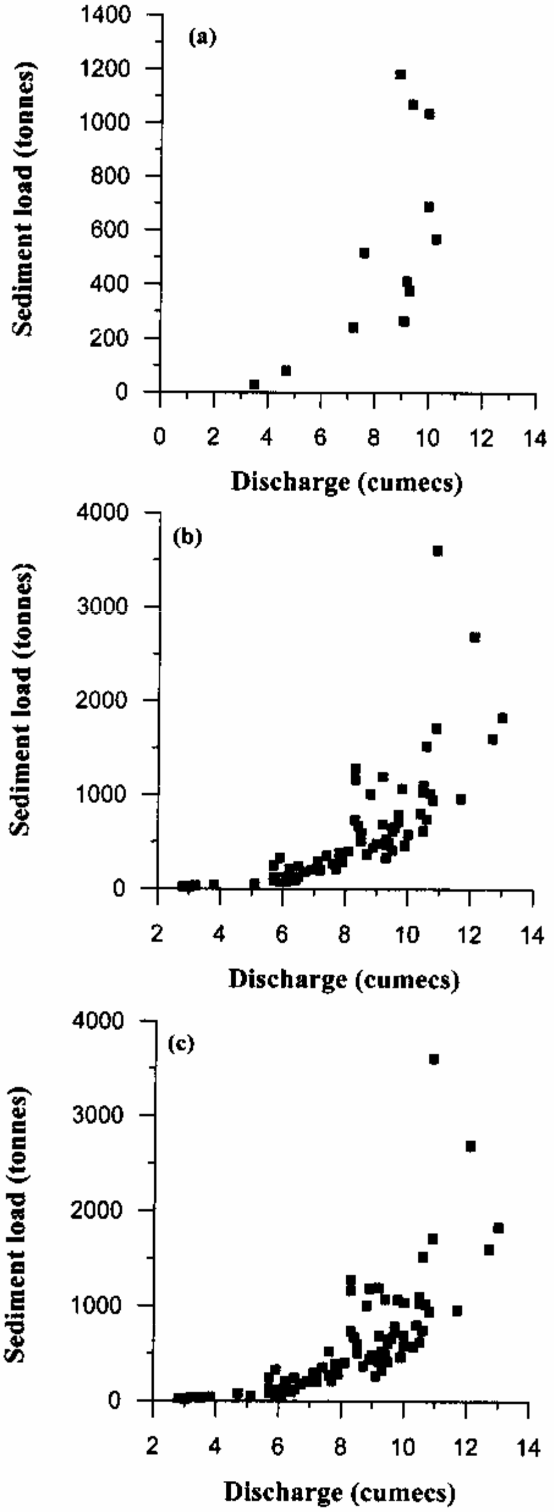

Figure 14 : Relationship between discharge and suspended sediment load for summer 1995 data : (a) for non rainy days, (b) for rainy days, (c) for all days.

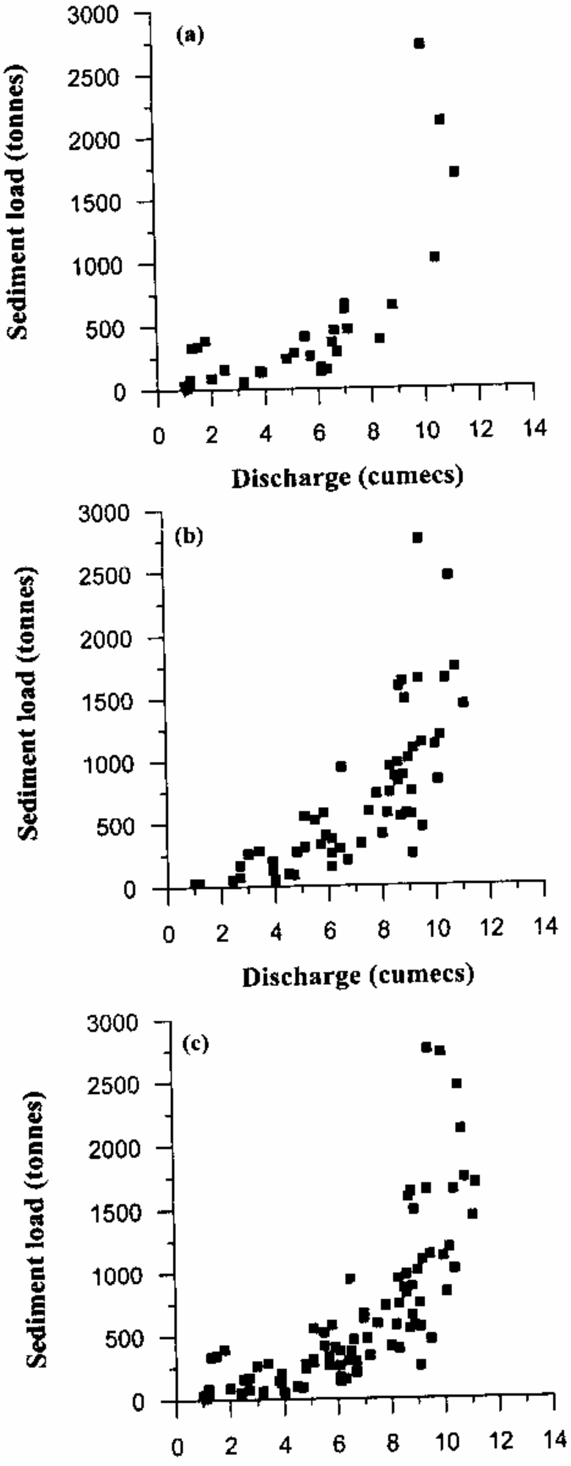

Figure 15 : Relationship between discharge and suspended sediment load for summer 1996 data : (a) for non rainy days, (b) for rainy days, (c) for all days.

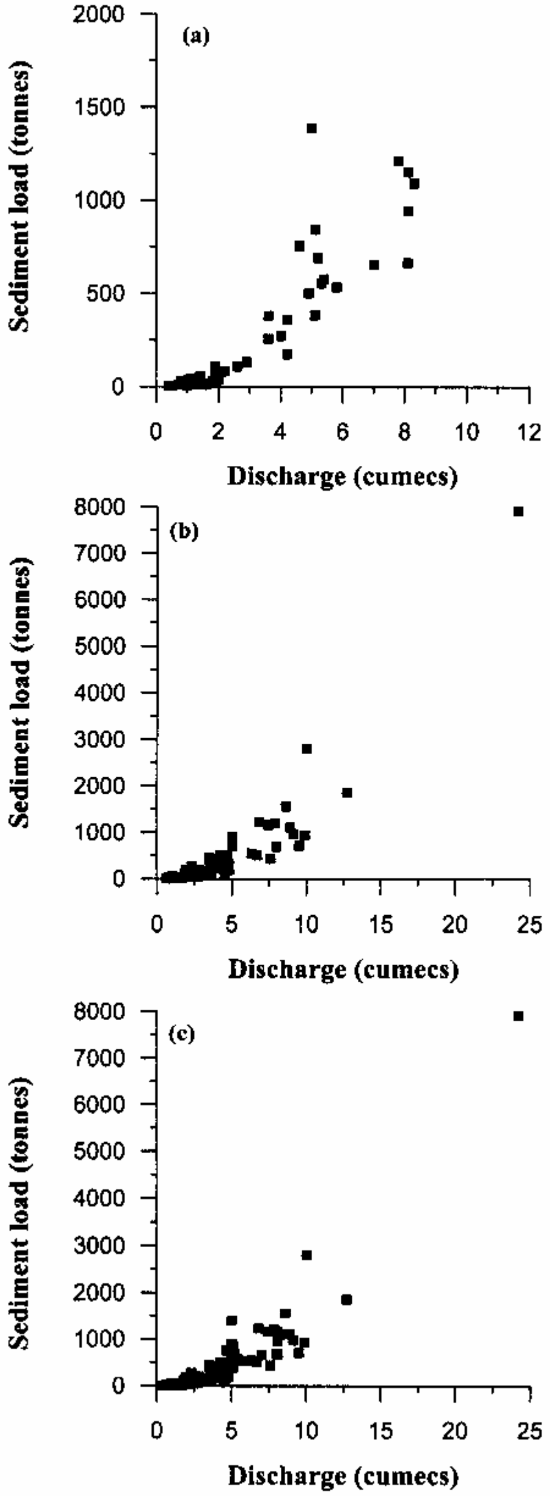

Figure 16 : Relationship between discharge and suspended sediment load for summer 1997 data : (a) for non rainy days, (b) for rainy days, (c) for all days.

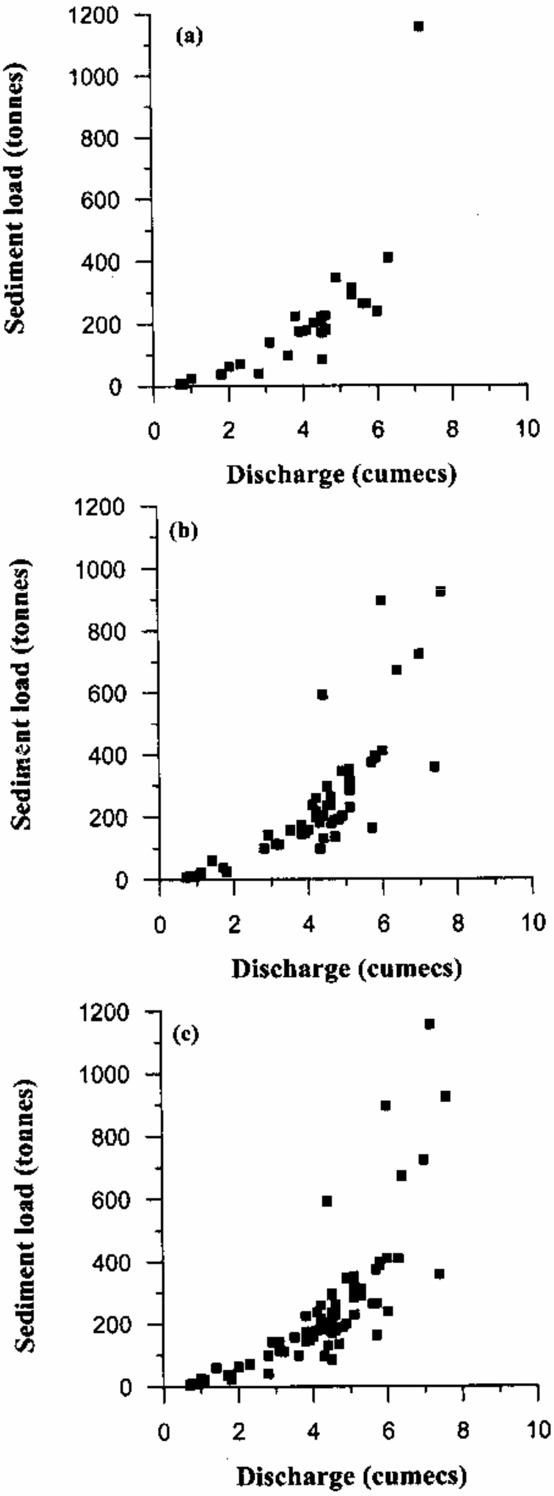

Figure 17 : Relationship between discharge and suspended sediment load for summer 1998 data : (a) for non rainy days, (b) for rainy days, (c) for all days.

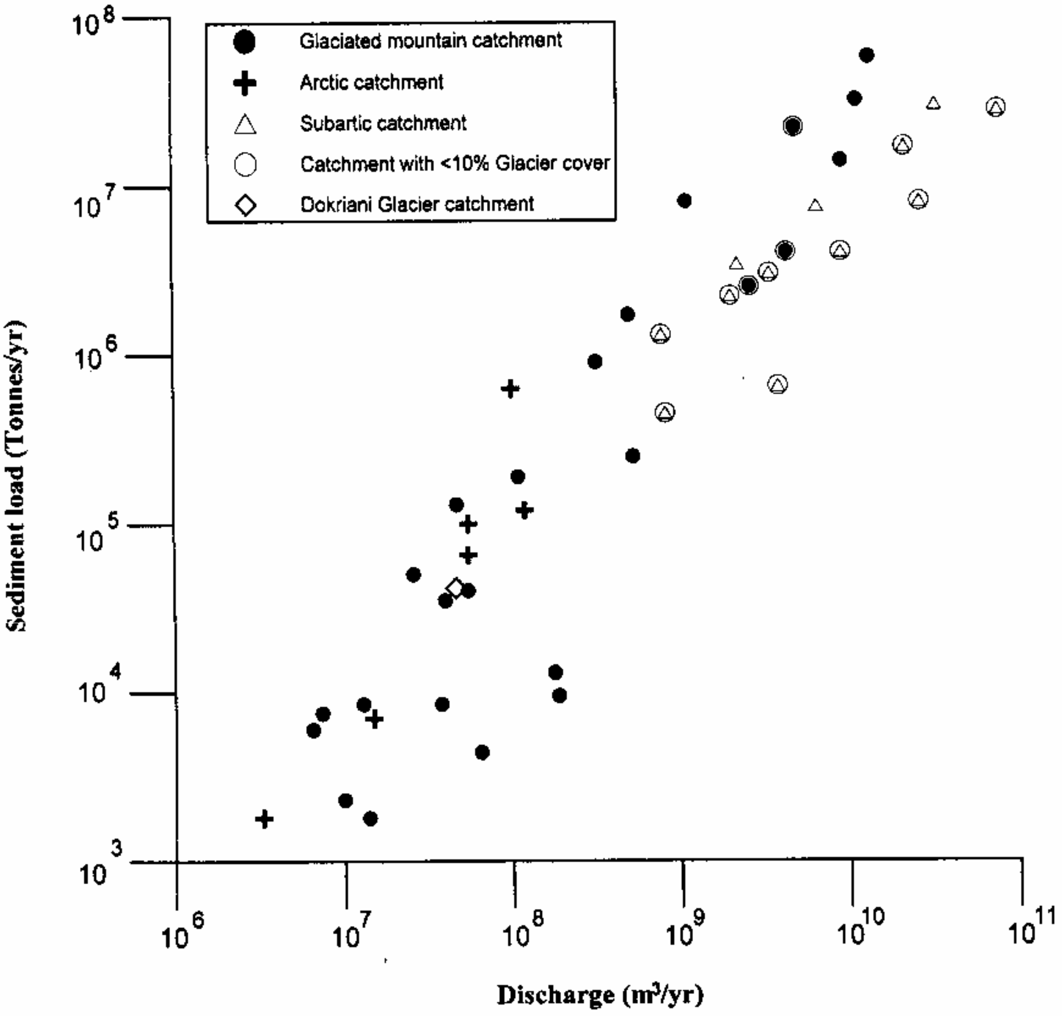

Figure18: Relationship between annual discharge volume and sediment load for various drainage basins (Gurnell and Clark, 1987). Data from a Himalayan glacier basin (Dokriani Glacier basin, 60% glaciated) is also illustrated in this figure.

data set of glaciers in different regions of the world. The Dokriani glacier basin is a mountain basin having about 60% area covered by the glacier. The relationship between annual discharge and suspended sediment load of the Dokriani glacier matches well with the trend reported for other glaciated areas and also fits well in the range of data reported earlier.

12.3 Suspended sediment particle size distribution

Particle size distribution is an attempt to determine the relative proportions of the different grain sizes in a given sample of sediment. Sediment samples collected from the Dokriani glacier melt stream near the snout of glacier were filtered by using preweighed Millpore 0.45μm filter paper. Particle size analysis was carried out by using Malvern Master Sizer E. Master Sizer E gives the results in 32 size classes, ranging from 0.5 μm to 600 μm. In the present study the results are grouped into six categories Particle size distribution curve for different summer months for 1997 and 1998 is shown in Figure 19 & 20. Temporal variation in the content of clay, fine silt, medium silt, coarse silt, fine sand and coarse sand is also presented.Variation in distribution on the weekly basis for the ablation period is given in Table 11 and 12. Monthly distribution is shown in Table 13, 14, 15 and 16. Average percentage of clay, silt and sand for 1997 was observed to be 1, 64 and 35%, whereas corresponding values for 1998 were 2, 71 and 27%. Evidently, for both 1997 and 1998 summer seasons silt content was highest followed by sand. As such clay content was found negligible for both years. Coarse silt content was found maximum, i.e., 32 and 33 % in 1997 and 1998, respectively. Figure 19&20 shows that the percentage of clay, fine silt and medium sand do not change much during the ablation season (June to September), whereas medium silt, coarse silt and fine sand vary marginally from month to month. Broadly it can be concluded that in the beginning of glacier melt season, percentage of silt was less (or sand is higher) as compared to other months, which increases in the mid of melt season and further lower down in the end of melt season. In both years silt was found maximum in the month of July, which can be explained by high melt water runoff which removes sediment from the larger surface area the glacier and its bed as well. Similarly lower melt rate causes to lesser amount of silt in the suspended sediment in comparison to other months.

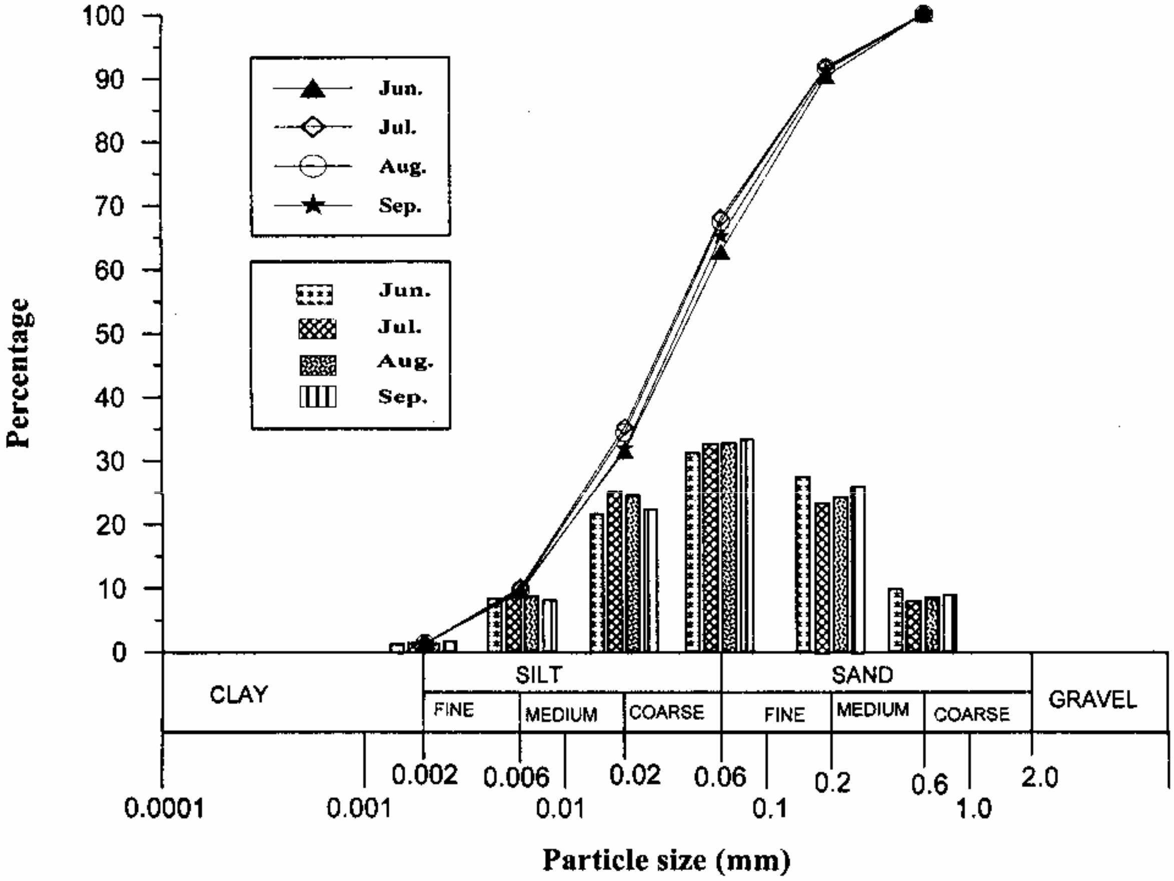

Figure19: Particle size distribution of the suspended sediment observed during ablation period in 1997 in Dokriani Glacier melt stream near the snout of glacier.

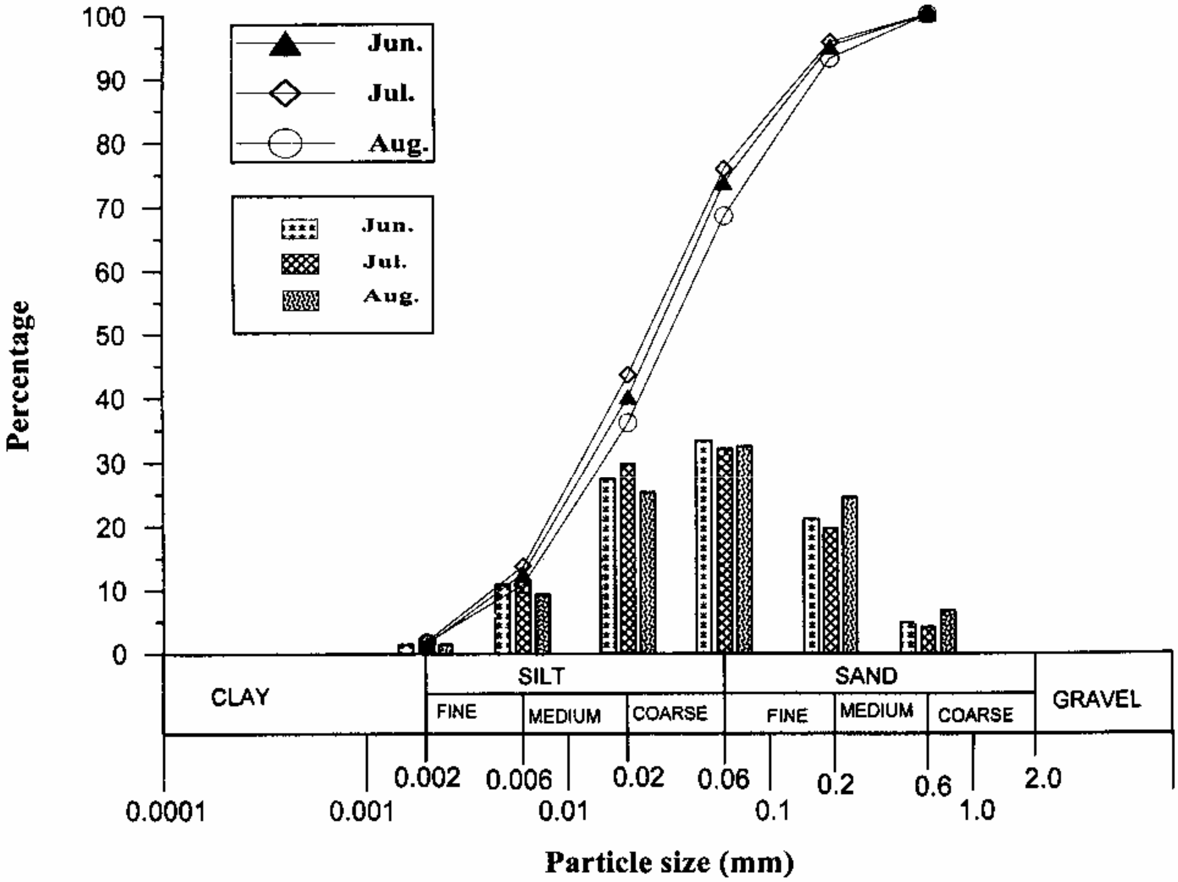

Figure 20: Particle size distribution of the suspended sediment observed during abalation period in 1998 in Dokriani Glacier melt stream near the snout of glacier.

Table 11: Weekly percentage distribution of suspended sediment particles in different sizes near the snout of the Dokriani glacier during summer 1997.

Period	Clay	Silt			Sand	
	(%) (<0.002mm)	Fine silt (%) (0.002-0.006mm)	Medium silt (%) (0.006-0.02mm)	Coarse silt (%) (0.02-0.06mm)	Fine sand (%) (0.06-0.2mm)	Medium sand (%) (0.2-0.6 mm)
01-07,Jun.1997	0.86	7.26	19.80	31.03	29.75	11.28
08-14,Jun.1997	1.75	12.19	26.38	31.26	21.16	7.26
15-21,Jun.1997	1.28	7.86	22.03	31.36	26.74	10.73
22-30,Jun.1997	1.08	6.68	18.96	31.22	32.30	9.76
01-07,Jul.1997	1.42	9.17	24.95	31.43	25.23	7.80
08-14,Jul.1997	1.31	8.61	26.22	32.78	23.18	7.90
15-21,Jul.1997	1.51	9.21	26.73	35.07	21.06	6.42
22-31,Jul.1997	1.30	7.82	22.85	31.77	25.36	10.90
01-07,Aug.1997	1.52	9.52	25.53	33.67	21.28	8.48
08-14,Aug.1997	1.35	7.59	25.68	34.97	23.16	7.25
15-21,Aug.1997	1.20	7.55	21.62	30.42	29.42	9.79
22-31,Aug.1997	1.46	8.86	25.78	32.85	22.95	8.10
01-07,Sep.1997	1.40	8.54	22.87	32.50	25.79	8.90
08-14,Sep.1997	1.13	7.71	22.07	34.04	26.31	8.74

Table 12: Weekly percentage distribution of suspended sediment particles in different sizes near the snout of the Dokriani glacier during summer 1998.

Period	Clay	Silt			Sand	
	(%) (<0.002mm)	Fine silt (%) (0.002-0.006mm)	Medium silt (%) (0.006-0.02mm)	Coarse silt (%) (0.02-0.06mm)	Fine sand (%) (0.06-0.2mm)	Medium sand (%) (0.2-0.6 mm)
08-14,Jun.1998	0.98	11.22	24.90	32.14	24.30	6.46
15-21,Jun.1998	1.61	10.79	28.61	34.90	19.90	4.19
22-30,Jun.1998	1.73	11.37	29.50	33.41	19.62	4.37
01-07,Jul.1998	2.22	12.91	32.30	33.36	16.31	2.91
08-14,Jul.1998	2.35	13.15	30.92	31.03	19.27	3.28
15-21,Jul.1998	1.56	11.68	30.26	31.60	19.60	5.30
22-31,Jul.1998	1.54	9.56	26.10	33.00	23.97	5.83
01-07,Aug.1998	1.44	9.10	24.67	32.36	25.53	6.90
08-14,Aug.1998	1.45	9.12	25.85	32.50	24.28	6.80
15-21,Aug.1998	1.59	9.51	25.82	32.66	24.52	5.90
22-31,Aug.1998	1.56	9.49	25.02	32.10	23.93	7.90

Table 13 : Monthly percentage distribution of suspended sediment particles in different sizes near the snout of the Dokriani glacier during summer 1997.

Month	Clay	Silt			Sand	
	(%) (<0.002mm)	Fine silt (%) (0.002-0.006mm)	Medium silt (%) (0.006-0.02mm)	Coarse silt (%) (0.02-0.06mm)	Fine sand (%) (0.06-0.2mm)	Medium sand (%) (0.2-0.6 mm)
June,1997	1.24	8.50	21.79	31.22	27.49	9.76
July,1997	1.39	8.70	25.19	32.76	23.71	8.26
Aug,1997	1.38	8.38	24.65	32.98	24.20	8.41
Sept,1997	1.26	8.13	22.47	33.27	26.05	8.82

Table 14: Monthly percentage distribution of suspended sediment particles in different sizes near the snout of the Dokriani glacier during summer 1998.

Month	Clay	Silt			Sand	
	(%) (<0.002mm)	Fine silt (%) (0.002-0.006mm)	Medium silt (%) (0.006-0.02mm)	Coarse silt (%) (0.02-0.06mm)	Fine sand (%) (0.06-0.2mm)	Medium sand (%) (0.2-0.6 mm)
June,1998	1.44	11.13	27.67	33.48	21.27	5.01
July,1998	1.92	11.83	29.90	32.25	19.79	4.33
Aug,1998	1.51	9.30	25.34	32.38	24.56	6.87

Table 15: Monthly percentage distribution of clay, silt and sand in the suspended sediment samples collected near the snout of the Dokriani glacier during summer 1997.

Period	Clay (%) (<0.002mm)	Silt (%) (0.002-0.06mm)	Sand (%) (0.06-0.6mm)
June,1997	1.24	61.51	37.25
July,1997	1.39	66.65	32.22
Aug.,1997	1.38	66.01	32.61
Sept.,1997	1.26	63.87	34.87

Table 16: Monthly percentage distribution of clay, silt and sand in the suspended sediment samples collected near the snout of the Dokriani glacier during summer 1998.

Period	Clay (%) (<0.002mm)	Silt (%) (0.002-0.06mm)	Sand (%) (0.06-0.6mm)
June,1998	1.44	72.28	26.28
July,1998	1.92	73.98	24.12
Aug.,1998	1.51	67.02	31.44

The fluvially transported sediment consisting of silt-and clay-sized grains is called 'washload', which is traditionally associated with bare hill slope source areas (Reid and Frostick, 1994). The average value of washload which consists of clay and fine silt particles is computed to be 10 and 12% of total suspended sediment sample for 1997 and 1998, respectively. Chikita (1993) reported the percentage of washload (silt and clay <0.63 mm) to be more than 90% in the suspended sediment samples from the Peyto Creek, Canada, fed by the Peyto glacier. The Peyto creek basin geology is Precambrian and Cambrian argillite, limestone and dolomite. It is noticed that washload content into suspended sediment was very much less in the Dokriani Glacier melt stream as compared with Peyto Glacier melt stream.

13.0 CONCLUSIONS

The presence of glaciers in basin is considered one of the important source of sediment into the pro glacier stream. In the high mountain regions, glaciers scour the mountain slopes and transport rock and boulders to the lower valleys. Estimation of sediment transported in the streams becomes very important for planning, designing and operating the hydropower schemes in the Himalayan region. Quantification of suspended sediment load in the catchment area is, therefore, significant especially during the peak summer/monsoon period, as its increased quantity, due to enhanced melting or the precipitation inputs, may be detrimental to the turbines, besides resulting siltation in the reservoirs which directly reduces the capacity of reservoirs. Present study deals with quantification of sediment concentration, load and yield and erosion rate for Dokriani glacier basin. The sources of sedimentation in the glacier melt streams and processes associated with sediment generation and transport in the glacierized area are also discussed in brief in this report.

The concentration of suspended sediment in the melt stream varied from 80-3830 ppm during melt period, while suspended sediment load was observed in the range of 6 to7916 tonnes during melt period. The suspended sediment concentration begins to increase as the discharge increases from June onward. A very high quantity of sediment is transported from the glacierized basins. Mean monthly values of concentration for in June, July, August and September were observed 452, 933, 965 and 275 ppm, respectively. Average suspended sediment load transported in corresponding months was 3607, 18733, 20951 and 1794 tonnes, proving 45085 tonnes during ablation period. Both sediment concentration and load were found maximum in August followed by July. About 88% of the total sediment load was transported in the months of July and August. Mean monthly sediment concentration in the months of July and August was found about two times that of June, and about three times that of September. Sediment yield from this glacier is found very high as compared to the sediment yield at lower altitudes from the Himalayan basins. Movement of glacier, slumping of the heavily sediment laden portal ice into the stream, occurrence of good rainfall, landslides and rockslides in the ablation zone and near the snout of glacier, are considered responsible for such high suspended sediment load in the glacier melt stream.

Suspended sediment yield for the melt period is computed to be about 2800 t $km^{-2}yr^{-1}$, which is comparable with glacierized basins in the Pamir region. The erosion for Dokriani glacier basin is estimated to be about 2.0 mm for the ablation period, which is higher than the erosion rate reported by other investigators for the glacierized basins in Europe.

The size distribution analysis shows that average percentage of clay, silt and sand was found 1.4, 67.3 and 31.3%, indicating maximum content of silt followed by sand. There was No significant variation in the content of clay, slit and sand was found during the ablation period. Both sediment concentration and load were poorly correlated with discharge. However, relationship between discharge and sediment load was improved when monthly data were used.

There are very limited studies carried out to estimate sediment load and to determine the size distribution of suspended particles for the Himalayan glaciers where flow is highly dominated by the snow and ice melt runoff. There is need to extend such studies in the high altitude region of different Himalayan basins. Today our knowledge of the processes associated with suspended sediment generation and delivery in mountainous streams is limited. Erosion beneath a glacier is still a quite unknown part in glacial research.

References

Akbarov, A. A. and others (1979) Lednik Abramova, leningrad, Gidrometeoizdat.

Alekseyev, G. A. (1971) Ob'yektivnyye metody vyravnivaniya i normalizatsii korrelyastionnykh svyazey ,Objective methods of leveling and normalizing of correlative relationships, Leningrad.

Anbalgan, R. (1996) Hazards of erosion and sedimentation due to cloudburst in small catchnents-a case study from Kumaun Himalayas, India. In: Proceedings of the International Conference on Eco-hydrology of High Mountain Areas, Kathmandu, Nepal, pp. 433-438.

Anonymous, (1986) Annual soil and water and conservation report for Satluj catchment under centrally sponsored scheme of soil conservastion in the catchment of river valley projects, 1984-85 & 1985-86, department of Forest and Conservation, Government of Himachel Pradesh, Shimla, pp. 41.

Arnborg, L., H. J. Walker and J. Peippo (1967) Suspended load in the Colville River, Alaska, 1962, Geograf. Annals, Vol. 49, pp. 131-144.

Babu,R., K. G. Tejwani, M. C. Agrawal and L. S. Bhushan (1978) Distribution of erosion index and Iso-erodent map of India, Indian Journal of Soil Conservation, Vol. 6, No. 1, pp. 1-14.

Bagnold, R. A. and O. Barndorff-Nielson (1980) The pattern of natural size distributions, Sedimentrology, Vol. 27(2), pp. 199-207.

Baverage, J. P. and J. K. Culbertson (1964) hyperconcentration of Suspended Sediments, Journal of Hydraulics Division, Amer. Soc. Civil Eng., Vol. 90(HY6), pp. 117-128.

Bemporad, G. A., J. Alterach, F. F. Amighetti, M. Paviani, I. Saccardo (1995) A distributed approach for sediment yield evaluation in alpine regions. Journal of Hydology, Vol. 197, pp. 370-392.

Bemporad, G. (1994) Use of radar derived rainfall mearurements for improving runoff predictions. In: R. Rosso, A. Peano, I. Becchi, G.A. Bemporad(Editors), Advances in Distributed Hydrology, Water resources Publications, Fort Collins Co., pp. 307-326.

Benson, M. A. (1965) Spurious correlation in hydraulics and hydrology, proceedings of the American Society of Civil Engineers, Journal of Hydraulics Division, Vol. 91, No. HY4, pp. 35-42.

Bezinge, A. M., J. Clark, A. M. Gurnell and J. Warburton (1989) The management of sediment transported by glacial meltwater streams and its significance for the estimation of sediment yield, Ann. Glaciol, Vol. 13, pp. 15.

Bogen, J. (1996) Erosion rate and sediment yield of glaciers, Ann. Glaciol, Vol. 22, pp. 48-52.

Bogen, J. (1991)) Erosion rate and sediment Transport in Svalbard, in Gjessing, Y. Hagen, J.O. Hassel, K. A. Sand, K. Wold, B. (Eds) Arctic hydrology Present and Future Tasks, Norwegian National Committee for Hydrology Report No. 23, Oslo. pp. 147-158.

Bogen, J. (1989) Glacial sediment production and development of hydro-electric power in glacierised areas, Ann. Glacio. Vol. 13, pp. 6-11.

Bogen, J. (1980) The hysteresis effect of sediment transport systems, Nor. Geogr. tidsskr., Vol. 34(1), pp. 45-54.

Bogen, J. (1979) Suspenderte sedimenters kornfordelling under transport, In Enell, M. and G. Gahnstrom, Eds. 7, Nord. Symp. on Sediments, Anebod, Sweden, May 24-27,1979, Lund, Lunds Universitet, Limnologiska Institutet, pp. 111-123.

Bruijneel, A. and N. Bremmer (1989) Highland-lowland interactions in the Ganges-Brahmputra river basin: a review of published literature, International Centre for Integrated Mountain development(ICIMOD), Occasional paper no. 11, Kathmandu, Nepal, pp. 136.

Bruk, S. (1992) The management challenge in sediment research, 5th Int. Symp. On river Sedimentation, Karlsruhe.

Bundela, D. S., R. Singh and K. Mishra (1995) Sediment yield modeling for small watersheds in Barker river valley. Inst. Of Eng. (1) Jr., Vol. 76, pp. 22-25.

Carson, B. (1985) Erosion and sedimentation processes in the Nepalese Himalaya, ICIMOD Occasional Paper No. 1, Kathmandu, Nepal: ICIMOD.

Carson, M. A., C. H. Taylor and B. J. Grey (1973) Sediment production in small application watershed during spring runoff: the Eaton basin, 1970-1972, Can. Journal Earth. Sciences, Vol. 10, pp. 1709-1734.

Central Board of Irrigation and Power (CBIP) (1981) Sedimentation studies in reservoirs, Vol.

II. CBIP Tech. Report No. 20, New Delhi, India.

Central Soil and Water Conservation Research and Training Institute (CS&WC) (1991) Evaluation of hydrological data, Indo-German bilateral Project on watershed managment, Soil and Water Conservation Division (CS&WI), Ministry of Agriculture, New Delhi, India.

Christiansen, C., P. Blaesild and K. Dalsgaard (1984) Reinterprating "segmented" grain-size curves, Geo. Mag., Vol. 121(1), pp. 47-51.

Church, M.(1972) Bafflin Island Sandurs: a study of Arctic fluvial processes, Canada Geological Survey Bulletin-216.

Chikita, K. (1996) Suspended sediment discharge from snow-melt: Ikushunbetsu river, Hokkaido, Japan, Journal of Hydrology, Vol. 186, pp. 295-313.

Chikita, K. (1993) A comparative study on suspended sediment discharge initiated by snow or glacier melting, Sediment problems: Strategies for monitoring, prediction and control (proceeding of Yokohama Symposium, IAHS Publication, No. 217, pp. 257-267.

Collins, D. N. (1979a), Sediment concentration in melt waters as an indicator of erosion processes beneath an alpine glacier , Journal of Glaciology, Vol. 23, pp. 247-257.

Collins, D. N. (1979b), Quantative determination of the subglacial hydrology of two alpine glaciers , Journal of Glaciology, Vol. 23, pp. 347-361.

Collins, D. N., S. I. Hasnain (1994) Runoff and sediment transport from the glacierized basins at the Himalayan scale Alpine glacier project working paper 15, University of Manchester, U. K.,pp. 14.

Collins, D. N. and S. I. Hasnain (1995) Runoff and sediment transport from the glacierized basins at the Himalayan scale, Effects of scale on interpretation and management of sediment and water quality, IAHS Publication, no. 226, pp. 17-25.

Das, D. D. C., Y. P. Bali and R. N. kaul (1981) Soil conservation in multipurpose river valley catchments. Problems, Programme approaches and effectiveness, Indian Journal of Soil Conservation, Vol. 9(1), pp. 5-26.

Daydov, L. K. (ed) (1967) krupneyshie ledniki sredneyazii-ledniki fedchenko i zeravshanskiy, Rezul'taty meteorologicheskikh i gidrologicheskikh issledovaniy,(The largest Glaciers of central

Asia - Lednik Fedchenko i zeravshanskiy. result of meteorological and hydrological investigations).

Department of Agriculture and Cooperation(1982) Soil Conservation Problem Approach and Progress in India, Soil Conservation Division, Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India.

Deoja, B., M. Dhital, B. Thapa and A. Wagner (1991) Mountain Risk Engineering Handbook, Parts 1&2, Kathmandu : International Centre for Integrated Mountain Development , Kathmandu.

Dickinson, W. T., R. P. Rudra and Clark, D. J. (1986) A delivery ratio approach for seasonal transpot of sediment, IAHS Publication, Vol. 159, pp. 237-252.

Dos, I. C., M. Pais-Cuddou and N. C. Rawal (1969) Sedimentation of reservoirs, Journal of the irrigation and drainage division, ASCE, Vol. 95, No. IR3, pp. 415-429.

Drewry, D (1986) Glacial geological processes, Arnold, London, pp. 257.

Dune, T. (1977) Evaluation of erosion conditions and trends In guidelines for watershed management, FAo Conservation Guide No. 1, Rome, pp. 53-83.

Dune, T., W. Thang and B. F. Aubry (1991) Effect of rainfall, vegetation and microtopography on infiltration and run-off, Water Resources Research, Vol. 27(9), pp. 271-285.

Elwell, H. A. (1981) A soil loss estimation technique for southern Africa. In: Soil Conservation Problems And Prospects, Wiley, pp. 281-292.

Embleton, C. and A. M. King (1975) Glacial Geomorphology, Arnold, London, pp. 573.

Everest, R. (1832) Some observations on the quantity of earthy matter brought down by the Ganga river, Royal Asiatic Society, Bangal, pp. 238-242.

Fenn, C. R. and B. Gomez (1989) Particle size analysis of the sediment suspendeed in a proglacial stream: Glacier de Tsijiore Nouve, Switzerland, Hydro. Processes, Vol. -3, pp. 123-135.

Ferguson, R. I. (1984) Sediment load of the Hunza river, In: K. J. Miller(ed.), International Karakoram Project 2, Cambridge University Press, cambridge, pp. 581-598.

Fort, M. (1987) Geomorphic and hazards mapping in the dry continental Himalaya: 1:50,000 maps of Mustang District, Nepal, Mountain Research And Development, Vol. 7(3), pp. 222-238.

Fukushima, Y., M. Suzuki, T. Otha, H. Motoyama, K. Kawashima, H. Kubota and O. M. Bajracharya (1987) The hydrological data of Langtang valley, Nepal Himalaya, Bull. Glacier Res. Vol. 5, pp. 115-120.

Gardner, J. S. (1986) Recent fluctuation of Rakhiot glacier Nanga Parbat, Punjab Himalya, Bull. Glacier Res, Vol. 32(112), pp. 527-529.

Garde, R. J. and U. C. Kothyari (1987) Sediment yield estimetion , J. Irrig. and Power (india) Vol. 44(3), pp. 97-123.

Gupta, G. P. (1980) Soil and water conservation in the catchment of river valley projects, Status report, Indian Journal of Soil conservation, Vol. 8(1), pp. 1-7.

Gurnell, A. M. and M. J. Clark (1987) Glacio-fluvial Sediment Transfer- An Alpine Perspective. John Wiley & Sons, U.K.

Gurnell, A. M., D. Hannah and D. Lawler (1996) Suspended-sediment yield from glacier basins, IAHS Publication, No. 236, pp 97-104.

Gurnell, A. M., A. J. Hodson, M. J Clark,J. Bogen,J. O. Hagen and M. Tranter (1994) Water and sediment discharge from glacier basins: An Arctic and Alpine comparison,IAHS Publication, Vol. 242, pp. 325-334.

Gurnell, A. M. (1987) Suspended-sediment, A. M. Gurnell and M. J. Clark (Eds.) Glacio-fluvial Sediment Transfer, Johan Wiley & Sons Ltd., pp. 305-354.

Gurnell, A. M. (1982) The dynamics of suspended sediment concentration in an Alpine pro-glacial stream network, International Association of Hydrological Sciences Publication 138(Genral Assembly at Exeter 1982- Hydrological Aspects of alpine and high-Mountain Areas), pp. 319-330.

Guy, H. P. (1964) A analysis of some storm-period variables affecting stream sediments transport, Geological Survey Prof. Paper, Vol. 462-E, pp. 1-46.

Harbor, J. and J. Warburton (1992) Glaciation and denudation rates, Nature, pp. 356-751.

Hasnain, S. I. and D. S. Chauhan (1993) Sediment transfer in the glacio-fluvial environment Ba Himalayan prespective, Environment geology, Vol. 22, pp. 205-211.

Hassian, S. I. and R. J. Thayyen (1999) Discharge and suspended-sediment concentration of meltwaters, draining from the Dokriani glacier, Garhwal Himalaya, India, Journal of Hydrology Vol. 218, pp. 191-198.

Heidel, S. G. (1956) The progressive lag of sediment concentration with flood wave, Trans. Am. Geophysics Union, Vol. 37, pp. 56-66.

Hodkins, R. (1996) Seasonal trend in suspended sediment transport from an Arctic glacier, and implications for drainage system structure, Ann. Glaciol., Vol. -22, pp. 147-151.

Hodson, A. (1994) Climate hydrology and sediment transfer processes interactions in a sub-polar glacier basin, Svalbard, PhD Thesis, University of Southampton, pp. 257.

Hodson, A., A. M. Gurnell, M. Tranter, J. Bogen, J. O. Hagen and M. Clark (1998) Suspended sediment yield and transfer processes in a small high-Arctic glacier basin, Svalbard, Hydrological processes, Vol. 12, pp. 73-86.

Holeman, J. N. (1968) The sediment yield of major rivers of world, Water Resourses Research, Vol. 4, No. 4, pp. 737-747.

Hrissanthou, V. (1986), Mathematical model for the computation of sediment yeild from a basin, IAHS Publication, Vol. 159, pp. 393-411.

Humphery, N. F. and C. F. Raymond (1994) Hydrology, erosion and sediment production in a surging glacier: Variegated Glacier, Alaska, 1982-83, Journal of Glaciology, Vol. 40, No. 136, pp. 539-552.

Humphery, N. F., C. F. Raymond and W. Harrison (1986) Discharge of turbid water during mini-surges of Variegated Glacier, Alaska,U.S.A. Journal of Glaciology, Vol. 32, No. 111, pp. 195-207.

Iken, A. and R. A. Bindschalder (1986) Combined measurements of subglacial water pressure and surface velocity of Findelengletscher, Switzerland: conclusions about drainage system and sliding mechanism, Journal of glaciology, Vol. 32(110), pp 101-119.

Indian Council for Agricultural research (ICAR) (1984) Guidelines and Status of Hydraulic and Sediment Management of Watersheds in selected River Valley Catchments, Water and Soil Conservation division, Ministry of Agricalture, New Delhi, India.

Ives, J. D. and B. Messerli (1989) The Himalayan Dilemma: Reconciling Development and Conservation,United Nations University and Routledge, Londonl.

Jansson, M. (1988) A global survey of sediment yield, Geografiska Annaller, 70A, pp. 81-98.

Jiang, D., L. Qi, and J. Tan (1981) Soil erosion and conservation in the Wudding river valley, China, In Morgan, R. P. C. (ed.), Soil Conservation Problems And Prospects, John Wiley & Sons Ltd. , U. K. , pp. 461-479.

Joglekar, D. V. (1965) irrigation research in India, Centrl board of Irrigation and Power Publ. India, No. 78.

Jones, K. R. (1981) Arid Zone Hydrology, FAO, Rome.

Jose, C. S. and D. C. Das (1982) Geomorphic prediction models for sediment production rate and Inters priorities of watersheds in Mayurakshi catchment, Proc. of the Int. Sym. on hydrological aspects of mountations watersheds, School of Hydrology, Uni. of Roorkee, India, Nov. 4-6, Vol. 1, pp. 15.

Joshi, V. and G. C. S. Negi (1995) Garwhal Himalaya mein vibhinn bhumi upyog wale do Jalagamo mein jal utpadan udhyayan, Jalvigyan evam Jal Sansadhan par Rasthriya Sangosthi, pp. 303-307, National Institute of Hydrology,Roorkee.

Kamb, B. Raymond, C. F. Harrison, W. D. Engelhardt, H. Echeleyer, K. A. Humphery, N. Burgnan, M. M. Pfeffer, T. (1985) Glacier surge mechanism: 1982-1983 surge of Variegated glacier, Alaska, Science, Vol. 227, pp. 469-479.

Karlsen, E. (1991) Variations in grain size distribution of suspended sediment in a glacial meltwater stream, Austre ? Oksteendbreen, Norway. Journal of Glaciology, Vol. 37, pp. 113-119.

Khosla, A. N. (1951) Appraisal of water resources, Proceedings, UNS Conference on the Conservation and Utilization of Resources, No. 4, U. N. department of Economic Affairs, New York, N.Y., pp 64-77.

Kobayashi, D. (1986) Separation of the snowmelt hydrograph by stream conductance Journal of Hydrology, Vol. 84, pp. 157-165.

Kostzewski, A. Kaniecki, A. Kapuscinski, J. Klimczak, R. Stach, A. Zwolinski, Z. (1989) The dynamics and rate of denudation of glaciated and non-glaciated catchments in central Spitsbergen, Polish Polar Res. , Vol. 10 pp. 317-367.

Kothyari, U. C. (1996) Erosion and sedimentation problems in India. In: Proceedings of International Symposium on Erosion and Sediment Yield. Exeter, U. K. IAHS Publication No. 236, pp. 531-539 .

Kothyari, U. C., A. K. Tewari and R. Singh (1994) Prediction of sediment yield, J. Irrig. Drain Eng., ASCE Vol. 20(6), pp. 1122-1131.

Krenke, A. N., and V. F. Suslov eds. (1980) Lednik Abramova (Lednik Abramova), Leningrad, Gidrometeoizdat.

Kurashig, Y. (1993) Mechanism on delayed appearance of peak suspended sediment concentration in a small river, Trans. Jpn. Geomorph. Union, Vol. 14, pp. 385-405.

Lanzhou Institute of Glaciology and Geocryology, (1980) Study and survey of Batura glacier in the Karakoram mountain (In Chinese) Science pres, Bejing.

Liestol, O. (1967) Storbbreen glacier in Jotunheimen, Norway, Norsk Polarinstitute Skrifter, Nr. 141.

Loughran, R. I. (1976) The calculation of suspended sediment transport from concentration versus discharge curves, Catena, Vol. 3, pp. 45-61.

Marcus, W. A. (1989) Lag-time routing of suspended sediment concentrations during unsteady flow, Geological Society of Am. Bul. Vol. 101, pp 644-651.

Meybeck, M. (1976) total mineral dissolved transport by world major rivers, Hydrol. Sci. Bull., Vol. 21, pp. 265-284.

Milliman, J. D. and R. H. Meade (1993) Worldwide delivery of river sediments to the Oceans, Journal of Geology, Vol. 91, pp. 1-19.

Mishra, N. and T. Satyanarayan (1991) A new approach to pridict sediment yield from small ungauged watersheds, Jr. of Inst. of Engg. (India) Agri. Engg. Div., Vol. 73, pp. 30-36.

Morris, G. L. (1995) Reservoir sedimentation and sustainable development in India, In. Proc. Sixth Int. Symp. on river Sedimentration, New Delhi, India, pp. 57-61.

Mukherjee, B. K., D. C. Das, S. Singh, C. S. Prasad and J. C. Samual (1985) Statistics: Soil and water conservation in India, Ministry of Agri. and rural development, Goverment of India, New Delhi.

Murthi, B. N. (ed.)(1977) Sedimentation studies in reservoirs Vol. 1, Central Board of Irrigation and Power Tech. report No. 20, New Delhi, India.

Narayana, D. V. V. (1987) Downstream impects of soil conservation in the Himalayan region. Mountain Research and Development , Vol. 7(3), pp. 287-298.

Narayana, D. V. V. and R. Babu (1983) Estimation of soil erosion in India, Journal of Irrigation and Drainage Engineering, ASCE, Vol. 109(4), pp. 419-434.

Nautiyal, A.R. and G. C. S. Negi (1994) Multipurpose tree spacies with potential for introduction in Agroforestry system in the Himalayan mountains, P.Singh, P. S. Pathakand B. Gopal (eds.) Agroforestry Systems for Degraded Lands, Oxfors and IBH Publishing Co.,New Delhi,pp. 269-280.

Ohta, T., Y. Fukushima, M. Suzuki, T. Otha, H. Motoyama, K. Kawashima and H. Kubota (1987) Suspended-sediment yield in a glaciated watershed of Langtang valley, Nepal Himalaya, Bull. Glacier Res. Vol. 5, pp. 19-24.

Osterm, G. (1975) Sediment transport studies at selected glacier stream in Norway 1969, in Johnson, P. G. (Ed.), Fluvial Processes: Cueillette et Analysis des Donnees, Occasional Papers, Department of Geography and regional Planning , University of Ottawa, 3, University of Ottawa Press, pp. 5-23.

Osterm, G., C. W. Bridge and W. F. Ranne (1967) Galcio-hydrology, discharge and sediment transport in the Decade glacier area, Baffin Island, N.W.T., Geografiska Annaler, Vol. 49A, pp 268-282.

Oyarzum, C. E. and L. Pena (1995) soil erosion and Overland flow in forested areas with pine plantations at coastal mountain range, Central Chile,Hydrological Processes, Vol. 9, pp. 111-118.

Pal, S.K. and K. Bagchi(1975) Recurrence of floods in Brahmputra and Kosi Basin: A study in climatic geomophology, Geographical Review of India, Vol. 37,pp. 242-248.

Patnaik, N. (1981) Role of soil conservation and deforestation for flood moderation, In: Proc. Conference on Flood Disasters, New Delhi, India.

Rainwater, F. H. and H. P. Guy (1961) Some observations on the hydrochemistry and sedimentation of the Chamberlain Glacier area, Alaska, U. S. Geol. Surv. Prof. Pap, 414-C.

Rao, S. V. N., K. S. Ramasastri and R. N. P. Singh (1996) A simple monthly model for snow dominated catchments in Western Himalayas. Nordic Hydrology, Vol. 27(4), pp. 255-274.

Rao, S. V. N., M. V. Rao, K. S. Ramasastri and R. N. P. Singh (1997) A study of Sedimentation in Chenab Basin in Western Himalayas. Nordic Hydrology, Vol. 28, pp. 201-206.

Rawat, J. S. amd M. S. Rawat (1994) Accelerated erosion and denudation in the nana kosi watershed, Central Himalya, India, Part I: sediment load, Jr. of Mountain research and develpment, Vol. 14(1), pp 25-38.

Raymo, M. E. and W. F. Ruddiman (1992) Tectonic forcing of Late Cenozoic climate, Nature, Vol. 359, pp. 117-122.

Reid, I. and L. E. Forstic (1994) Fluvial sediment transpot and deposition , In: K. Pye (Editor), sediment transport and depositional processes, Blackwell Sceintific Publications, Oxford, pp. 89-155.

Reid, I. and L. E. Forstic (1987) Flow dynamics and suspended sediment properties in arid zone flash floods, Hydrol. Processes J., pp. 239-252.

Repp, K. (1988) The hydrology of Bayelva, Spitsbergen, Nordic Hydrology, Vol. 19, pp. 259-268.

Reynolds, R. C. and N. M. Johnson(1972) Chemical weathring in the temprature glacial environments of the Northern Cascade Mountains. Geochimica Cosmochimica Acta, Vol. 36, pp. 537-554.

Richards, K. S. (1984) Some observations on suspended sediment dynamics in Storbregrova, Jotunheim, Earth Surface Processes and Landforms, Vol. 9, pp. 101-112.

Rodda, J. C. (1976) Basin studies, In: Facts of Hydrology, Wiley, pp. 257-297.

Roth, G., F. Siccardi and R. Rosso (1989) Hydrodynamic description of the erosional development of drainage patterns. Water Resour. Res., Vol. 25(2), pp. 319-332.

Rothlisberger, H. (1972) Water pressure in intra and subglacial channels, Journal of glaciology, Vol. 11, No. 62, pp. 177-203.

Sadykov, K.G. (1976) rezhim stka vzveshennykh i vlekomykh nanosov u istokov lednikovykh rek razlichnykh rayonov Sredney Azii (Regime of suspended and bed load sediment run-off near glacier river heads in different regions of central Asia).

Sarin, M.M., S. Krishnaswami, J. R. Trivedi and K. K. Sharma (1992) Major ion chemistry of Ganga source waters: Weathering in the high altitude Himalayan , Proceeding of Indian Academy of Sciences (Earth. Plant. Sci.), Vol. 101, No. 1, pp. 89-98.

Shangle, A.K.(1991) Hydrographic surveys of Indian reservoirs. In: Course Material for Workshop on Reservoir Sedimentation, sponsored by IRTEC, China and UNESCO, New-Delhi, India, pp.2.9.1-2.9.16

Sharma, C. K. (1987) the problem of sediment load in the development of water resources in Nepal,Mountain Research and Development, Vol. 7(3), pp. 316-318.

Sharma, K. D. (1996) Soil erosion and sediment yield in the Indian arid zone. In: Proceedings of International Symposium on Erosion and Sediment Yield, Exeter, U. K.IAHS Publication No. 236, pp. 175-181.

Sharma, K. D. and D. C. Josi (1982) Sedimentation and its control in Nadis in the Indian arid zone- A case study, J. Arid Environ., Vol. 5, pp. 269-276.

Sharma, P. D., A. K. Goel and R. S. Minhas (1991) Water and sediment yields into the Satluj river from the high Himalaya. Mountain Research and Development, Vol. 11, pp. 87-100.

Shcheglova , O. P. (1974) Zemletryaseniya i glyatsial'nyy smyv (na primere) r. Vakhsh) [Earthquake and glacial washing-off (Vakhsh river as example)]. Trudy Sredneaziatskogo Regional'nogo Nauchno-Issledovatel'skogo Gidrometeorologicheskogo Instituta 14(95): 134-141.

Shcheglova , O. P. (1981) Sediment Transport from the Glacier Zone, Central Asia. Annals of Glaciology, Vol. 2, 1981, pp 103-108.

Shcheglova , O. P. and O. P. Chizhov (1981) Sediment Transport from the Glacier Zone, Central Asia. Annals of Glaciology, Vol. 2, 1981, pp. 103-108.

Shcheglova , O. P. and N. G. Lebedeva (1978) Glyatsial'nyy smyv i temperatura vozdukha na poverkhnosti lednikov [Glacial washing-off and air temprature at the glacier surface].

Shchetinnikov, A. S. (1976) Ledniki basseyna reki Pskem [glaciers of the Pskem river basin].

Singh, G., Ram Babu, Narain, P., Bhushan, L.S., and Abrol, I.P.(1990) Soil erosion rates of India, In: Proc. International Symposium on Water Erosion, Sedimentation and Resources Conservation , Dehradun, India, pp. 32-38.

Singh, P., K. S. Ramsastri, U. K. Singh, J. T. Gergan and D. P. Dobhal (1995) Hydrological characteristics of the Dokriani glacier in the Garhwal Himalayas, Hydrological Sciences, Vol. 40, pp. 243-257.

Singh, P. (1991) A temperature lapse rate study in Western Himalayas, Hydology Journal of IAH , Vol. XIV, pp. 156-162.

Singh, P. and S. K. Jain (1993) Snow and Glacier contribution in Chenab basin upto Akhnoor, NIH Publication, CS/AR 131, Roorkee, India.

Singh, P. and N. Kumar (2000) Study of suspended sediment transfer in the Dokriani glacier melt stream, Technical report, National Institute of Hydrology, Roorkee.

Singh, P., and K. S. Ramasastri (1999) Temporal distribution of Dokriani glacier melt runoff and its relationship with meteorological parameters, Project Report, National Institute of Hydrology, Roorkee.

Singh, P., K. S. Ramasastri and N. Kumar (1995) Topghraphical influences on precipitation distribution , in different ranges of Western himalayas, Nordic hydrology, Vol. 26, (4/5), pp. 260-286.

Singha, R.S. and P.N.Gupta (1982) Assessment of Siltation in Tehri Reservoir, International Symposium on Hydrological Aspects of Mountainous Watersheds, 4-6 November 1982, UOR, Roorkee (India), pp VII 60-VII 66.

Small, R. J. (1987) Morain sediment budgets, In: A. M. Gurnell and M. J. Clark, (ed.) Glacio-fluvial sediment transfer-An alpine prospective, Wiley, Chichester, U. K., pp. 165-197.

Sorriso- Valvo, M., R. B. Bryan, A. Yair, F. Iovino and L. Antronico (1995) Impact of Afforestation on Hydrological Response and sediment production in a small Calabrian Catchment. Catena 25, pp. 89-104.

Stern, C. R., K. KIngfield, D. Schelling, N. S. Virdi, K. Futa, Z. E. Peterman and H. Amini (1989) The Bhagrithi leucogranite of the high Himalaya (Garhwal India), age, petrogenessis and tectonic implications, In : L. Maliconico Jnr. and R. J. Lillie (ed.) Tectonics of Western Himalaya, Geological Society of America.

Subramanian, V. (1993) sediment load of Indian rivers, Current Sciences, Vol. 64(11,12), pp. 928-930.

Sundd, D. K. (1991) Sediment transport in Indian rivers, Proceeding of Reginol Training course on reservoir sedimentation and contrl, Central Wateer Commission, New, Delhi, India, pp. 189.

TejWani, K. G. (1987) Sedimentation of reservoir in the Himalayan region-India, Mountain Research and Development, Vol. 7(3), pp. 323-327.

Tempany, H. and D. H. Grist (1958) Introduction to Tropical Agriculture, Longmans, London.

Tranter, M. Brown, G. H. Hodson, A. J. Gurnell, A. M. (1996) hydrochemistry as an indicator of subglacial drainage system structure: a comparision of Alpine and sub-polar environments, Hydrological processes Vol. 10, pp. 541-556.

Tronov, M. V. (1966) Ledniki i Klimat [Glacier and climate], Leningrad, Gidrometeoizdat.

Valdiya, K. S. (1985) Accelerated erosion and landslide-prone zones in the central Himalaya, Concepets and Strategies, Gyanodaya Prakashan, Nainital, pp. 122-38.

Varsheney, R.S.(1975) Text of Engineering Hydrology, Nemchand brothers publication, Roorkee, India, pp. 24.

Varsheney, R.S.(1979) Engineering Hydrology, Nemchand brothers publication, Roorkee, India, pp. 917.

Varsheney, R. S., S. Prakash and C. P. Sharma (1986) Varriation of sediment rate of reservoirs in Himalayan region with catchment, Proc. of 53rd R & D Session, CBIP Bubhaneshwar, India, Technical session IX paper.

Vatne, G., B. Etzelmuller, R. S. Odegard and J. L. Sollid (1992) Glacio-fluvial sediment transfer of a sub-polar glacier, Erikbreen,Svalbard, Stuttgarter Geograph. Stud., Vol. 117, pp. 253-266.

Verma , B., K. G. Tejwani, M. V. Kale and A. P. Patel(1968) evalution of different cropping patterns for runoff and soil loss in Ravine lands, Journal of the Indian Society of Agronomy, Vol. 13, pp. 262-270.

Vivian, R. and J. Zumstein (1973) Hydrologe sous-glaciaire au glacier d=Argentere (Mont Blanc, France), in Symposium on the hydrology of Glaciers, (Preceeding of the Cambridge Symposium, 7-13 September 1969), International Association of Scientific Hydrology Publication 95, pp. 53-64.

Vohra, C. P. (1981) Himalayan glaciers, In: J. S. LAll and A. D. Moddie (ed.), The Hiamlaya, Oxford University Press, pp. 138-151.

Walling, D. E. (1977) Assessing the accuracy of suspended sediment rating curves for a small basin, Water Resources Research, Vol. 13, No. 3, pp. 531-538.

Walling, D. E. (1988) Erosion and sediment yield research- some recent perspectives, Journal of Hydrology, Vol. 100, pp. 113-141.

Walling, D. E. and P. W. Moorehead (1987) Spatial and temporal variation of the particle-size characterstics of fluvial suspended sediment. Geogr. Ann., Vol. 69A(1), pp. 47-59.

Walling, D. E. and B.W. Webb (1983) Patterns of sediment yield. In: background to palaeohydrology (ed. by K. J. gregory), Wiley, pp. 69-100.

Warburton, J. (1990) An Alpine proglacial fluvial sediment budget, Geografiska Annaler,72A(3-4), pp. 261-272.

Williams, G. P. (1989) Sediment concentration versus water discharge during single hydrological events in rivers, Journal of Hydrology, Vol. 111, pp. 89-106.

Wischmeier, W. H., D. D. Smith (1978) Predicting rainfall erosion losses, A guide of conservation planning US Dep. Agric. Handb., pp. 537.

Wood, P. A. (1997) Controls of variation in suspended sediment concentration in the river Rother, West Sussex , England, Sedimentrology, Vol. 24, 437-445.

Yamada, T. (1993) Glacier lakes and their outburst floods in the Nepal Himalaya, Water and Energy Commission Secretariat, Kathmandu, Nepal pp. 37.

Zheng Benxing (1989) the influence of Himalayan uplift on the development of Quaternatry glacierrs, Zertschrift fur geomorphologie Suppl. Bd, Vol. 76, pp. 1-89.

Ziegler, T. and H. C. Olsen (1974) Materialtransport-undersokelser i norske bre-elver 1972, Norges Vassdragsog Elektrisitetsvesen, Vassdragsdirektoratet, hydrologisk Avdeling, Rapport 2-74.

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